Miscellaneous Paper D-95-2
August 1995

US Army Corps
of Engineers
Waterways Experiment
Station

Dredging Operations Technical Support Program

Dredging-Induced Near-Field Resuspended Sediment Concentrations and Source Strengths

by Michael A. Collins, Southern Methodist University

Prepared for Headquarters, U.S. Army Corps of Engineers

The D-series of reports includes publications of the Environmental Effects of Dredging Programs:

Dredging Operations Technical Support

Long-Term Effects of Dredging Operations

Interagency Field Verification of Methodologies for Evaluating Dredged Material Disposal Alternatives (Field Verification Program)

PRINTED ON RECYCLED PAPER

Dredging Operations Technical Support Program

Miscellaneous Paper D-95-2
August 1995

Dredging-Induced Near-Field Resuspended Sediment Concentrations and Source Strengths

by Michael A. Collins

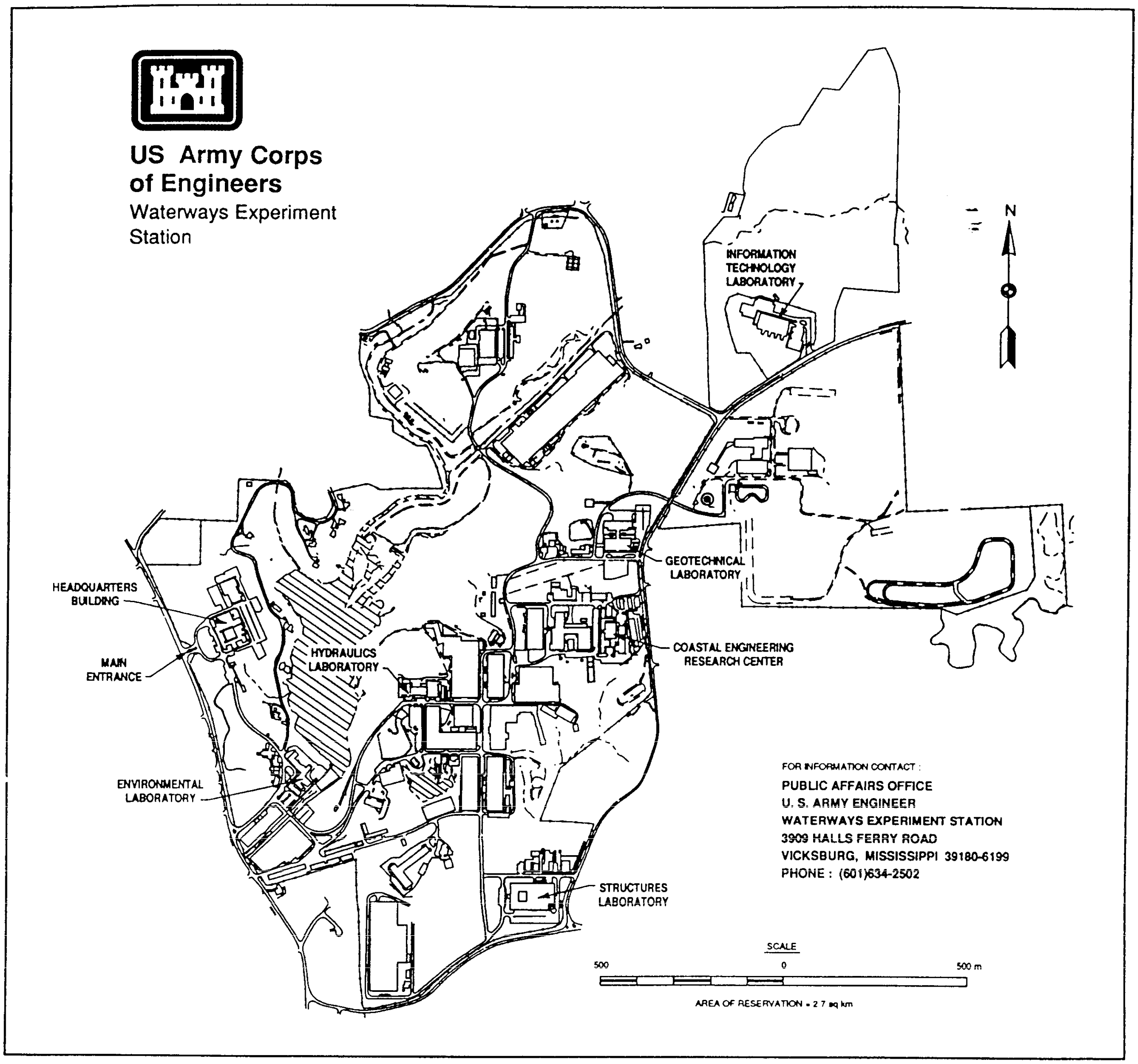
School of Engineering and Applied Science
Southern Methodist University
Dallas, TX 75222

Final report

Approved for public release; distribution is unlimited

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Monitored by U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road, Vicksburg, MS 39180-6199



Waterways Experiment Station Cataloging-in-Publication Data

Collins, Michael A.

Dredging-induced near-field resuspended sediment concentrations and source strengths / by Michael A Collins ; prepared for U.S. Army Corps of Engineers ; monitored by U.S. Army Engineer Waterways Experiment Station.

229 p. : ill. ; 28 cm. -- (Miscellaneous paper ; D-95-2)

Includes bibliographic references.

1. Suspended sediments -- Environmental aspects. 2. Marine sediments -- Analysis. 3. Water quality -- Analysis. 4. Dredging. I. United States. Army. Corps of Engineers. II. U.S. Army Engineer Waterways Experiment Station. III. Dredging Operations Technical Support Program (U.S. Army Engineer Waterways Experiment Station) IV. Title. V. Series: Miscellaneous paper (U.S. Army Engineer Waterways Experiment Station) ; D-95-2.

TA7 W34m no.D-95-2

US Army Corps
of Engineers
Waterways Experiment
Station

Environmental Effects of Dredging Programs

Dredging Operations Technical Support

Report Summary

Dredging-Induced Near-Field Resuspended Sediment Concentrations and Source Strengths (MP D-95-2)

ISSUE: Dredging in riverine, lacustrine, and estuarine environments resuspends bottom sediments into the overlying water column. Dispersal of these resuspended sediments may pose water quality problems in waters near the dredging operations. Possible release of contaminants adsorbed on sediment particles, alteration of the physiocochemical properties of overlying or nearby waters, and the resettling of sediments in environmentally sensitive waters distant from the dredging operation are potential problems.

RESEARCH: This research entailed field studies to assess the suspended sediment concentrations in the water column in the vicinity of various dredge types. These concentration data were combined with conceptual models for resuspended sediment source strength geometries and velocity patterns to estimate sediment source strengths for cutterhead and clamshell dredges.

SUMMARY: The resuspended sediment source models developed in this study, although unverified, provide a starting point for a more thorough analytical evaluation of the entire resuspension, transport, and deposition process.

AVAILABILITY OF REPORT: The report is available on Interlibrary Loan Service from the U.S. Army Engineer Waterways Experiment Station (WES) Library, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199; telephone (601) 634-2355.

To purchase a copy, call the National Technical Information Service (NTIS) at (703) 487-4780. For help in identifying a title for sale, call (703) 487-4780. NTIS report numbers may also be requested from the WES librarians.

About the Authors: Mr. Michael A. Collins is a Consulting Engineer with Woodward-Clyde Consultants of Houston, TX. For further information about the Dredging Operations Technical Support Program, contact Mr. Thomas R. Patin, Program Manager, at (601) 634-3444.

Contents

Preface vi

Conversion Factors, Non-SI to SI Units Measurement viii

1—Introduction 1

Background 1
Purpose 1
Scope 2
Methodology and Limitations 2
Data sources and characteristics 2
Concentration analysis and source modeling 3

2—Dredge and Dredging Site Features 4

Types of Dredges 4
Near and Far Flow Fields and Sediment Sources 5
Site and Sediment Characteristics 5
Sediment Concentration Data 6
Field data collection procedures 6
Background concentrations 7
Dredging-induced concentrations 7

3—Resuspended Sediment Concentrations 9

Cutterhead Suction Dredges 9
Concentrations at cutterhead 10
Factors influencing resuspension 11
Resuspended sediment concentration model 13
Development of dredging parameter F_F and F_D 15
Effects of cutterhead and sediment size 16
Effects of type of cut 17
Full-cut dredging function 21
General data correlation 27
Dustpan Dredge 28
Matchbox Dredge 29
Hopper Dredges 30
Nonoverflow operating mode 30
Overflow operating mode 31
Clamshell Dredges 32
Factors influencing resuspended sediment levels 32

Data analysis 34
Open clamshell source concentrations 36
Closed clamshell 38

4—Suspended Sediment Source Strengths 40

Features of Source Model Structure 41
Source geometry 41
Source concentration 41
Velocity structure 42
Model coefficients 42
Cutterhead Dredge 42
Source volume geometry 42
Velocity structure 43
Source strength 43
Clamshell Dredge 44
Source geometry 44
Fluid and suspended sediment motions 45
Source concentration 48

5—Summary 51

References 55

Tables 1-7

Appendix A: Notation A1

Appendix B: Abbreviations B1

Appendix C: Penetration Relations for Cutterhead Dredge C1

Appendix D: Background Concentrations at James River, 1982 . . . . . . D1

Appendix E: Dustpan Suction Dredge Concentrations
at James River, 1982 . . . . E1

Appendix F: Cutterhead Dredge Concentrations
at James River, 1982 . . . . F1

Appendix G: Background Concentrations at Savannah River, 1983 . . . . G1

Appendix H: Cutterhead Suction Dredge Concentrations
at Savannah River, 1983 . . . . H1

Appendix I: Background Concentrations at Calumet Harbor, 1985 . . . . . I1

Appendix J: Matchbox Suction Dredge Operating
Characteristics at Calumet Harbor, 1985 . . . . J1

Appendix K: Matchbox Suction Dredge Concentrations
at Calumet Harbor, 1985 . . . . K1

Appendix L: Cutterhead Suction Dredge Operating
Characteristics at Calumet Harbor, 1985 . . . . L1

Appendix M: Cutterhead Suction Dredge Concentrations
at Calumet Harbor, 1985 . . . . M1

Appendix N: Hopper Dredge Concentrations Above Background Concentrations at Grays Harbor, November 1983 . . . . N1

Appendix O: Background Concentrations at St. Johns River, 1982 . . . . O1

Appendix P: Closed-Bucket Clamshell Dredge Concentrations at St. Johns River, 1982 . . . . P1

Appendix Q: Open-Bucket Clamshell Dredge Concentrations at St. Johns River, 1982 . . . . Q1

Appendix R: Background Concentrations at Black Rock Harbor, 1983 . . . . R1

Appendix S: Open-Bucket Clamshell Dredge Concentrations at Black Rock Harbor, 1983 . . . . S1

Appendix T: Background Concentrations at Duwamish Waterway, 1984 . . . . T1

Appendix U: Open-Bucket Clamshell Dredge Concentrations at Duwamish Waterway, 1984 . . . . U1

Appendix V: Open-Bucket Clamshell Dredge Background and Dredging Concentrations at Lake City, 1984 . . . . V1

Appendix W: Closed-Bucket Clamshell Dredge Background and Dredging Concentrations at Lake City, 1984 . . . . W1

Appendix X: Background Concentrations at Calumet River, 1985 . . . . . X1

Appendix Y: Open-Bucket Clamshell Dredge Concentrations at Calumet River, 1985 . . . . Y1

SF 298

List of Figures

Figure 1. Schematics of cutterhead burial for various types of cuts 18

Figure 2. Full-cut dredging function F_F for cutterhead dredge 23

Figure 3. Cutterhead cutting type function F_D 26

Figure 4. Sediment resuspension predictions for cutterhead dredge operating at full-cut burial 28

Figure 5. Resuspended sediment concentrations observed behind a hopper dredge operating in Grays Harbor, Washington . . . 31

Figure 6. Relative resuspended sediment concentration versus distance for open bucket clamshell dredges 36

Figure 7. Open-bucket clamshell dredge correlation 39

Preface

The field studies discussed in this report were conducted by the Water Resources Engineering Group (WREG) (currently the Engineering Applications Branch (EAB)), Environmental Engineering Division (EED), Environmental Laboratory (EL), at the U.S. Army Engineer Waterways Experiment Station (WES) in Vicksburg, MS, sponsored by the Improvement of Operations and Maintenance Techniques (IOMT) Research Program under Work Unit 32433, "Contaminant Release Control During Dredging."

Final technical editing and publication of this report were conducted at WES under the sponsorship of the Dredging Operations Technical Support Program (DOTS), Mr. Thomas R. Patin, Manager. The DOTS Program is managed through the Environmental Effects of Dredging Programs (EEDP), Dr. R. M. Engler, Manager. Mr. Daniel E. Averett, Environmental Restoration Branch (ERB), EED, EL, managed the task area providing for completion of this report. Mr. Joe Wilson was Technical Monitor for Headquarters, U.S. Army Corps of Engineers.

This report was written by Dr. Michael A. Collins, formerly Professor of Civil Engineering, School of Engineering and Applied Sciences, Southern Methodist University, Dallas, TX, and currently with Woodward-Clyde Consultants, Houston, TX. Dr. Donald F. Hayes, formerly with WREG and currently with the Department of Civil Engineering, The University of Utah, Salt Lake City, was the immediate technical supervisor for the project. Administrative supervision was provided by Dr. John J. Ingram, Chief WREG/EAB; Dr. Raymond L. Montgomery, Chief, EED; and Dr. John Harrison, Chief, EL. The IOMT Program Managers were Messrs. E. Clark McNair, Jr., and Robert F. Athow, Hydraulics Laboratory, WES.

Final technical editing of this report was conducted during Fiscal Year 1993 by Dr. Hayes under an interagency support agreement between the University of Nebraska Water Research Center and ERB, and by Mr. Averett. Funding for the technical editing and report preparation was provided by the Dredging Contaminated Sediments: Techniques for Evaluating Resuspension and Release of Contaminants Task Area under the DOTS Program, managed through the Environmental Effects of Dredging Program (EEDP) by Mr. Averett. Technical review of this report was provided by Mr. Averett and Mr. Paul A. Zappi, WREG. Administrative supervision during the

agreement period was provided by Mr. Norman R. Francingues, Chief, ERB; Dr. Raymond L. Montgomery, Chief, EED; and Dr. John Harrison, Chief, EL.

At the time of publication of this report, the Director of WES was Dr. Robert W. Whalin. The Commander was COL Bruce K. Howard, EN.

This report should be cited as follows:

> Collins, Michael A. (1995). "Dredging induced near field resuspended sediment concentrations and source strengths," Miscellaneous Paper D-95-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Conversion Factors, Non-SI To SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic yards	0.7645549	cubic meters
degrees	0.01745329	radians
feet	0.3048	meters
inches	2.54	centimeters
gallons	3.785412	cubic decimeters
square feet	0.09290304	square meters
Note: Source Strength Conversion 1 (milligram/liter) (cubic feet/second) = 0.0283 grams/second		

1 Introduction

Background

Dredging in riverine, lacustrine, and estuarine environments introduces bottom sediments into overlying waters because of imperfect entrainment and incomplete capture of sediments resuspended during the dredging process and the spillage or leakage of sediments during subsequent transportation and disposal of the dredged sediments. Resuspension of bottom sediments and resulting dispersal may pose water quality problems in waters near the dredging operations. Possible release of contaminants adsorbed on sediment particles or residing in interstitial bottom sediment waters, alteration of the physicochemical properties of overlying or nearby waters, and the resettling of sediments in environmentally sensitive waters distant from the dredging operation are a few of the potential environmental problems.

Different types of dredges and dredging operations produce differing amounts of sediment resuspension. Predictions of resuspension and dispersal can provide a basis for improved operation and management of dredging activities. Such estimation requires information about the physical characteristics of the sediment being dredged and the type of dredge being considered and its particular operating characteristics. This report provides a physically based quantitative description of sediment resuspension in the close vicinity of certain types of dredges studied under the U.S. Army Corps of Engineers Improvement of Operations and Maintenance Techniques (IOMT) Research Program.[1]

Purpose

The amount of bottom sediments resuspended in the waters above, below, and around dredges can be described in terms of either (a) sediment concentrations in the vicinity of the dredges during their operation, or (b) rates of resuspended sediment generation at the source. The identification of parameters affecting such sediment concentrations and the characteristics of the

[1] For convenience, abbreviations are listed in Appendix B.

resuspended sediment sources provide insight into the impacts of dredging operations. Such identification should be an integral element in the mathematical description of the entire sediment resuspension, advection, and dispersion process occurring in the general vicinity of operating dredges. This report provides a field-based description of dredging-induced resuspended sediment concentrations and proposes certain mathematical models for dredge-induced resuspended sediment sources.

Scope

This report deals only with resuspension of sediments attributable to the actual dredging process and does not address the effects of sediment disposal or other coincidental factors (such as barge and boat traffic, marine construction, or dredge move-in and setup). Resuspended sediments introduced into the water column in the immediate vicinity of a dredge are subsequently dispersed to points near and far about the dredge by currents, tides, and fluid turbulence. In describing resuspended sediment concentrations and source strengths, this report focuses upon the sediment conditions found in the immediate vicinity of the dredge and considers only incidentally sediment levels at greater distances from the dredge.

Because of the complex factors that influence sediment resuspension, evaluation of field data is imperative for realistic description of the resuspension process and estimation of resuspended sediment source strengths. Field data gathered under the IOMT program are used in this report to describe the sediment concentrations in the close vicinity of dredge types. These concentration data are combined with conceptual models for resuspended sediment source geometries and velocity patterns to estimate sediment source strengths.

Methodology and Limitations

Data sources and characteristics

The present study uses information drawn from several sources (Hayes 1986a, 1986b; Hayes, McLellan, and Truitt 1988; Havis 1988; McLellan et al. 1989) on field studies conducted during the period of 1982 to 1985 at the nine dredging sites listed in Table 1. Depending upon the dredge type and particular site, the data provide information on site and flow conditions, suspended sediment concentrations at various distances and locations about the dredge, and dredge characteristics and operation.

Collection of reliable resuspended sediment data in large-scale field studies, such as the type conducted under the IOMT program, is inherently difficult and subject to many potential sources of both random and systematic error. To effect various analyses, considerable reliance upon temporal and spatial averaging was necessary to reduce data noise. Thus temporally and spatially variable effects arising from external effects such as tides and currents are not specifically identified in the results obtained. However, since the suspended sediment concentrations of interest are near the dredging operation, these factors should be of little importance.

Because of both the character and sometimes limited extent of the database used in various analyses, concentrations developed in this study should be viewed as preliminary until they are verified by additional field studies.

Concentration analysis and source modeling

The field-measured sediment concentrations are analyzed using physical and dimensional reasoning and statistical regression to provide, when possible, a quantitative correlation of resuspended sediment concentrations in the close vicinity of a dredge. Key physical parameters quantifying flow and site conditions, sediment properties, and dredge and dredging characteristics are used in the analysis. Resuspended sediment source models incorporating assumptions as to source geometry and flow patterns are formulated on the basis of physical reasoning, inferences from field data, and descriptions of dredging operations reported in IOMT studies. Source strengths are evaluated using these models in combination with the concentration correlations.

Consequently, resuspended sediment concentrations are based upon actual field data while sediment source strengths, on the other hand, incorporate both field data and assumptions about the features of the resuspension process. The resulting source strength values are mathematical deductions and not directly measurable. Their verification must be indirectly accomplished through comprehensive modeling of the flow field about a dredge. Thus the source strength models proposed in this report must remain speculative until verified by future investigations.

2 Dredge and Dredging Site Features

Resuspension of sediments by dredging is affected by dredge and dredging characteristics, properties of bottom and suspended sediments, and site-specific conditions such as bottom topography, ambient current, and water depth. As a necessary preliminary to consideration of these factors in the dredging-induced sediment resuspension process, this chapter provides a general description of the types of dredges operated during the IOMT studies, a generic description of the flow field about a dredge, a summary of the sediment characteristics at the dredging sites, and a discussion of the features of the sediment concentrations measured during the IOMT dredging studies.

Types of Dredges

Two general types of dredges have been studied under the IOMT program (Table 1): the hydraulic dredge, including cutterhead, matchbox, and dustpan dredge heads on unpropelled dredge plants along with a self-propelled hopper dredge; and the clamshell bucket dredge, including both closed and open bucket designs. Detailed descriptions of these various types of dredges have been provided by Arctic Laboratories et al. (1985), Herbich and Brahme (1991), the U.S. Army Corps of Engineers,[1] Montgomery and Raymond (1984), Peterson (1986), and Raymond (1982, 1984). Generally, hydraulic dredges rely upon a combination of mechanical digging and agitation by a dredgehead to dislodge the sediment and hydraulic suction to lift the dislodged sediment from the bottom. Hopper dredges also rely upon mechanical dislodgement and hydraulic suction as do other hydraulic suction dredges, but differ from other types of hydraulic dredges in that the dredge ship is self-propelled and better able to operate in open water environments. Clamshell bucket dredges rely primarily upon bucket impact, claw gouging and digging, and bucket closure to scoop up and bring bottom sediments to the surface.

[1] U.S. Army Corps of Engineers, Office of Civil Works. (n.d.). "Dredging," Engineering School Manual, The Engineering Center, Fort Belvoir, VA.

Near and Far Flow Fields and Sediment Sources

Sediments removed from the bottom by a dredging operation are either collected and entrained by the dredge, then hydraulically or mechanically removed from the dredging site, or introduced into the water column in the near vicinity of the dredge. Some sediments introduced into the water column and not removed by the dredge may resettle almost immediately in the vicinity of the dredging operation. Other sediments become distributed at various depths throughout the water column. Sediments that are introduced into the water column, that are not carried away by the dredge, and that do not immediately resettle, are considered to be the resuspended sediments. Once resuspended, these sediments are advected and dispersed in varying amounts in the flow field surrounding the dredge. Different types and sizes of dredges, different modes of operation, and different site conditions all result in differing amounts and rates of sediment resuspension.

Two zones can be identified in the dredging area (Hayes[1] 1986a): (a) the near field area immediately surrounding the dredge or dredge head and (b) the far field exterior to and generally surrounding this near field zone. The sediment concentrations in the near field are dominated by the mechanical and hydraulic actions of the dredge and its operation; current- and tidal-induced advection, dispersion, and settling dominate the sediment behavior in the far field.

The amount of resuspended sediment and its distribution in the immediate vicinity of a dredge can be viewed as the result of a source of resuspended sediment located at the dredge or dredgehead in the central core of the near field. This source produces a flux of resuspended sediment into the interior, central zone of the near field. Once in this near field, the resuspended sediment is conveyed outward in some fashion by a combination of advection, dispersion, and turbulence toward the outer edges of the near field area where it merges into a far field plume of suspended sediment.

Site and Sediment Characteristics

Table 1 provides a summary description of the dredging sites studied under the IOMT program. Both inland and coastal areas with a variety of current and salinity conditions are included. Of particular interest are the types of sediment at the sites. Generally, the soils are mixtures of clays and silts, often with high organic content and low specific gravity. The low specific gravity is reflective of the high organic content and sometimes significant amounts of oil and grease in the sediments.

---

[1] D. F. Hayes. (1987). "Removal of contaminated aquatic sediments using a cutterhead dredge," Unpublished paper, Department of Civil Engineering, Colorado State University, Ft. Collins, CO.

Sediment features that influence the magnitude and distribution of resuspended sediment in the near field water column common to all types of dredging operations are (a) the physical character of the sediments being dredged, as can be quantified by grain size and distribution and specific gravity (relative to the overlying waters) of the sediments, (b) the condition of the in situ sediments as reflected by in situ bulk density, void ratio, and similar physical measures, and (c) the physicochemical characteristics of the sediment or the overlying waters, such as salinity, which might affect colloidal behavior and consequent settling of sediment particles.

In the analyses described in this report, only median grain diameter (as determined by standard grain size analysis methods) and specific gravity of the in situ sediments are used to distinguish between sediment characteristics at the different dredging sites (Table 1); data availability precluded consideration of other factors. Even with restriction to these two physical parameters, however, available site data did not always provide specific information on median grain diameter or specific gravity. In the Calumet River study, a reasonable estimate of these parameters could be made using the data from the nearby Calumet Harbor study. The median grain size at the Savannah River site was estimated, on the other hand, by using data for the Savannah Harbor area presented in a study of dredging sites by Bartos (1977) as summarized by Herbich and Brahme (1991). The median grain size at the Black Rock Harbor site was estimated by extrapolation of partial grain size curves, which did not extend as low as the median grain size. Because of the small median grain size and the sometimes low specific gravity of the dredged sediments, settling velocities are small. (For example, a particle with a median grain size and specific gravity similar to that at the Calumet Harbor site has a fall velocity of 0.02 fps according to Stokes' law, while that of the Savannah Harbor site has only a 0.002-fps fall velocity.)

Sediment Concentration Data

Field data collection procedures

Detailed discussions on the field procedures for collecting and analyzing the suspended sediment data at the various dredging sites can be found in McLellan et al. (1989); Hayes, McLellan, and Truitt (1988); Hayes[1] (1986a); and Vann[2] (1983). In general, water samples were collected from various depths in both the far and near field areas surrounding the dredge during actual dredge operation at various radial distances and angles relative to the

[1] D. F. Hayes. (1987). "Removal of contaminated aquatic sediments using a cutterhead dredge," Unpublished paper, Department of Civil Engineering, Colorado State University, Fort Collins, CO.

[2] R. G. Vann. (n.d.). "James River, Virginia dredging demonstration in contaminated material (kepone), dustpan versus cutterhead," Report, U.S. Army Engineer District, Norfolk, Norfolk, VA.

dredge. At the sites where a cutterhead dredge was operating, the near field samples were collected from a multiple port sampling array located very near the cutterhead on the dredge ladder (see Table 2 for the relative location of sampling tubes on cutterhead dredges; also see Hayes, McLellan, and Truitt (1988) for a detailed description of a cutterhead dredge sampling array).

Background concentrations

Background suspended sediment concentrations (see Table 1 for representative values) were collected in a manner similar to that for the far field concentrations taken during dredging operations. The background samples for the near field were taken in the general vicinity of the actual dredge operation during a period of nondredging but at a time near the near field sampling with the dredge in operation (e.g., on the day immediately before that for which samples were taken during actual dredging). Background concentrations at points near the dredge or dredgehead were estimated by spatial and temporal extrapolation or interpolation of the measured background concentrations. These background concentrations at the various dredging sites are provided in Appendices D, G, I, O, R, T, V, W, and X.

Different techniques were used to estimate the background concentrations, depending upon the character and quantity of background data available. In some cases, a simple average of all measured data was used, while in other cases, horizontal and vertical variations of measured concentrations were considered. At some sites, background concentrations varied little, while at others, varying current and tidal flows resulted in significant variations. In all cases, the background concentrations were determined independently of the concentrations observed during dredging operations.

Dredging-induced concentrations

Bottom sediments disturbed or removed by the mechanical and hydraulic actions of a dredge are either entrained and collected by the dredge, then conveyed to some release or disposal point, or mixed with background suspended sediment to remain in the water column in and around the dredging operation until resettling at some possibly distant point some later time. The difference between measured total suspended solids concentration at a point and the estimated background suspended solids concentration at that same point is assumed to represent the increase in sediment concentration due to the dredging operation. This net concentration difference is the resuspended sediment concentration discussed in this study, for which concentration correlations and resuspended sediment source strengths are provided. Unless otherwise specified, all further mention of resuspended sediment concentration refers to this quantity. These concentrations will frequently be referred to as the observed or measured concentrations; it is recognized that such reference is not precisely true, since only total sediment concentrations were measured in the field. Such reference is made only as a convenience to easily identify the resuspended sediment concentrations computed from measured total concentrations by subtraction of an estimated background concentration.

However, while such a net concentration difference, in view of the level of precision possible in the IOMT field studies to date, is a very appropriate quantity for assessing dredging effects, it is recognized as not necessarily being the most accurate. Background sediments in the water column may have significantly different physical or chemical characteristics from those introduced into the water column by a dredging operation. Resuspended sediments may alter the flocculation characteristics of the background suspended sediment particles and thereby affect their settling behavior. Such effects could be accentuated by salinity levels independent of the dredging operation. Fortunately, such effects can be generally expected to be of secondary importance in the near field area where resuspension is dominated by large mechanical and fluid forces.

3 Resuspended Sediment Concentrations

Near field dredging-induced resuspended sediment concentrations are strongly dependent upon the type of dredge and its operation. Key dimensions, mechanical and hydraulic features, and operating characteristics of a dredge can be used in conjunction with sediment properties to broadly predict the varying levels of resuspended sediment concentrations that may exist in the close vicinity of a dredge. However, actual measurement of suspended sediment concentrations in the near field around an operating dredge is difficult and, for certain types of dredges, potentially dangerous. Consequently, estimation of resuspended sediment concentrations in the central regions of the near field flow zone about a dredge may require inference from concentrations at greater distances rather than being determined by direct measurement.

Near field resuspended sediment concentrations used for this study and the methods used for their determination from field measurements follow. For cutterhead and clamshell bucket dredges, these concentrations are correlated with dredge and dredge operating characteristics and sediment properties.

Cutterhead Suction Dredges

Three studies (Table 1) have specifically examined sediment resuspension by cutterhead dredges. The conditions at the sites and the operating conditions of the dredges at the three sites, collectively, span a wide range of conditions, thus making these studies potentially very useful for examination of a variety of factors influencing sediment resuspension. However, data collection in the earlier two of the studies (i.e., the James River and the Savannah River studies) was not as complete nor as controlled as in the later Calumet Harbor study. As a result, in comparison to the Calumet Harbor data, considerable apparent random error exists in the data for both the James River and the Savannah River studies. Conclusions based solely upon these data should therefore be viewed with caution. Conversely, more confidence can be placed in deductions about resuspended sediment concentrations based upon the Calumet Harbor data.

Concentrations at cutterhead

Cutterhead dredges agitate, loosen, and dislodge bottom sediments with a combination of mechanical digging and gouging by a multiblade, rotating cutterhead. Hydraulic suction forces draw sediment-enriched waters upward through and around the cutterhead blades into a suction pipe extending along the cutterhead ladder arm. Sediment resuspension results from the incomplete entrainment of the dislodged sediments. Conceptually, the source of resuspended sediments is the cutterhead itself.

Perfectly designed and operated cutters will introduce a sediment slurry that will be completely entrained by the flow to the dredge pump. However, spatially varying sediment properties and cutter operations inevitably lead to a sediment slurry that the pump cannot handle, resulting in sediment resuspension or release.

Suspended sediment concentrations were directly sampled using tubes at several points in the immediate vicinity of the cutterhead to withdraw samples. The number of sampling tubes varied from one to six, depending upon the sampling device design and condition. Sampling tubes sometimes became clogged with sediment, rendering them temporarily inoperative, as evidenced by abnormally large suspended sediment concentrations being measured. To avoid inclusion of data from such potentially unrepresentative data, outliers in the concentration data were statistically identified and discarded by excluding data more than two standard deviations from the mean of a data set; roughly 10 percent of the data at the Savannah River and James River sites were discarded. The remaining concentrations measured by the sampling tubes at the cutterhead were arithmetically averaged, after adjusting for background concentrations, to approximate a spatial average concentration at the cutterhead source for each set of conditions at the particular time of the sampling. Total suspended sediment concentrations (i.e., concentrations before subtraction of background concentrations) along with dredge operating characteristics are given in Appendices F, H, and M for the cutterhead dredges at the James River, Savannah River, and Calumet Harbor sites, respectively. Background concentrations for the James River site are given in Appendices D and F, while background concentrations for the Savannah River and Calumet Harbor sites are given in Appendices G and I, respectively. Appendix L provides additional operating features of the dredge at the Calumet Harbor site.

For the Savannah River and James River sites, the concentration data are values measured at various particular times during the course of the field study as dredge operating conditions varied. For the Calumet Harbor site, however, the data represent averages (as given by Hayes (1986a) and Hayes, McLellan, and Truitt (1988)) over a period of time when operating conditions were essentially constant; because of the well-controlled dredge operating conditions during the course of the Calumet Harbor study, such averages are meaningful. The operating conditions at the Savannah River and James River sites were not as well defined. In addition, since cutterhead swing speed and intake velocity data were incomplete for the James River site, estimated average values for these parameters, which do not reflect their actual variation, were used for analysis. In particular, the ladder arm swing speed at the James River site had to be estimated from dredge dimensions and reported average ladder arm swing times in the port and starboard directions. Hayes (1986a) previously developed a simple geometric model relating swing speed and cutterhead path to dredge dimensions; this model was applied to the swing time data at the James River site. This considerably reduced the ability to distinguish the dependence of resuspended sediment concentration upon various operating conditions at the James River site.

Factors influencing resuspension

Previous investigators have identified or suggested factors that influence the amount of sediments introduced into the water column immediately surrounding the cutterhead (Hayes (1986a) provides a concise review of cutterhead dredge studies). In addition to the characteristics of the sediments being dredged, the water depth in which the dredging is taking place, and the fluid motion in the general area of the dredge operation, several factors are specifically characteristic of cutterhead dredges that influence the amount of resuspension.

The speed and turbulence of the waters, and thus their potential for both eroding and scattering sediments, surrounding the dredge cutterhead are affected by the rotation of the cutterhead blades and the swing speed of the cutterhead ladder on which the cutterhead is supported. Variations in either of these speeds can be expected to influence the amount of resuspension. On the other hand, background velocities in the general vicinity of the dredge are not expected to significantly influence the amount of resuspension; the velocity field around the cutterhead and cutterhead ladder is a localized velocity field largely determined by the motion of the swinging cutterhead ladder.

Furthermore, previous investigators (e.g., Hayes, McLellan, and Truitt, 1988) have generally found that the direction of the ladder swing relative to the cutterhead blade rotation is also important, with more resuspension occurring when the ladder swing is in the same direction as the tangential velocity of cutterhead blades at their highest point. When the tangential velocity of the cutterhead blades at their highest point is in the same direction as the ladder swing, the cutterhead is "overcutting," i.e., the cutterhead blades are rotating downward into the mudline and into the yet-undredged sediments toward which the cutterhead ladder is advancing. When the ladder swing opposes the tangetial velocity of the cutterhead blades at their highest point, the cutterhead is "undercutting," i.e., the cutterhead blades are rotating upward and away from the sediments being dredged and away from undredged sediments toward which the cutterhead ladder is advancing.

An explanation for the higher resuspended sediment concentrations that occur during overcutting can be provided: a primary source of finer grained resuspended sediments is the residual sediments clinging to the cutterhead blades as they break the level of the mudline near the top of the cutterhead. These residual sediments are washed off the blades by the fluid motions over and around the blades above the level of the mudline. Near the top of the cutterhead above the mudline level, the tangential velocity of the blades will be in the same direction as the swing velocity when overcutting occurs. Thus the net blade velocity relative to the overlying waters is the summation of the tangential velocity of the cutterhead blades and the ladder swing speed; when undercutting occurs, the net velocity is the difference between these same two velocities. Consequently, the cutterhead blades experience a higher shearing velocity during the overcutting phase of the swing than during the undercutting phase.

The effects of the residual sediment clinging to the cutterhead blades and being subsequently washed off by the relative fluid motion past the cutterhead can be expected to be more pronounced in silt and clay sediments; the cohesiveness of such sediments promotes clinging of sediments to the cutterhead blades. Such effects may not be as pronounced in noncohesive sediments. The sediments at the cutterhead dredge sites in this study were predominantly silt and clay, as evidenced by their median grain size (Table 1); consequently, this description of the washoff phenomenon is consistent with the field conditions in this study.

These effects can be quantified by the introduction of a cutterhead ladder arm swing speed V_s and a tangential velocity (at the top of the cutterhead) of the cutterhead blades V_c computed from the angular velocity and maximum radius of the cutterhead.[1] When the cutterhead is undercutting, the net velocity V_t characteristic of the fluid motion tending to wash sediments off the cutterhead is $V_t = V_c - V_s$; when overcutting, the characteristic velocity is $V_t = V_c + V_s$.

On the other hand, an increase in the rate at which sediment-laden waters are drawn into the dredge suction pipe will tend to reduce the amount of sediments found around the cutterhead. A meaningful and useful characterization of this effect has been proposed by Hayes (1986a) and Hayes, McLellan, and Truitt (1988). The cutterhead is assumed to be surrounded, in view of the shape of typical cutterheads, by one-half of a prolate spheroid (i.e., a semi-ellipsoid) formed by the rotation of an ellipse about its major axis, with major and minor axes equal to the length and the maximum radius, respectively, of the cutterhead. The suction discharge passing across this surface determines an average characteristic cutterhead intake suction velocity V_i. In addition, the diameter of a sphere whose volume is equal to the volume of the total ellipsoid defines a characteristic size, L, of the cutterhead.

The degree of cutterhead burial in the bottom sediments as the cutterhead is swung back and forth has also been identified as a significant factor influencing resuspension. Previous studies suggest that full burial, with all other

[1] For convenience, symbols are listed in the notation (Appendix A).

factors being equal, results in the least resuspension. Less than full burial (i.e., partial cutting) apparently increases resuspension, as does more than full burial (i.e., buried cutting). The reason for increased resuspension during partial cutting can be explained by the fact that in partial cutting more of the cutterhead blades are exposed above the mudline; more exposure of the blades allows more opportunity for washoff of sediments clinging to the cutterhead blades. The increase in resuspension because of buried cutting is understandable (though difficult to evaluate), because buried cutting contributes to sloughing and cave-in along the dredging path.

The Savannah River study had partial- and buried-cut but no full-cut operation, while the Calumet Harbor and the James River studies had only full cuts (Table 2). Thus, as will be seen below, the Calumet Harbor and James River studies are used to provide the primary insight into full-cut operations. The Savannah River study data are used to provide a preliminary quantification of the increased resuspension of sediments induced by partial- and buried-cut dredging.

Resuspended sediment concentration model

Hayes, in earlier studies of the Calumet Harbor site (Hayes 1986a; Hayes, McLellan, and Truitt 1988), found a good correlation of resuspended sediment levels with the dimensionless parameters V_s/V_i and V_t/V_i. The dependence evidenced in this correlation was consistent with physical reasoning as to the expected impacts of the various velocity parameters V_s, V_t, and V_i. As discussed above, more confidence could be placed in the field data from the Calumet Harbor site than in the field data from the Savannah River and James River sites. Thus it was considered important that the basic behavior demonstrated by the correlation found by Hayes (1986a) for the Calumet Harbor study be reflected in any model for resuspended sediment concentration that might incorporate data from all three cutterhead dredge study sites. Hayes' previously found result was therefore a starting point for correlation of data from all three cutterhead dredge sites examined in this study.

Using dimensionless analysis, Hayes (1986a) was able to relate resuspended sediment levels at the Calumet Harbor site to powers of the dimensionless parameters V_s/V_i and V_t/V_i; reanalysis of Hayes' data confirmed this basic dependence. For the Calumet Harbor study the resuspended sediment concentrations can be represented by

$$C/(\rho \times 10^{-6}) = 10^{u}(V_s/V_i)^{v} \, (V_t/V_i)^{w} \tag{1}$$

in which

C = concentration of resuspended sediment, g/ℓ

ρ = density of waters above the mudline (assumed to be 1 g/cm^3 for calculations in this study), g/cm^3

V_s = swing speed, ft/sec

V_i = intake suction velocity through approximating semi-ellipsoid surface, ft/sec

V_t = tangential speed of cutterhead, ft/sec

and u, v, and w are regression coefficients found by linear regression of the logarithmic form of Equation 1 on the resuspended sediment concentrations at the Calumet Harbor site. Regression analysis on the 12 data sets for the Calumet Harbor site yields $v = 2.848$ and $w = 1.022$ (similar to the values found by Hayes (1986a) and $u = -1.050$ with a correlation coefficient r^2 of 0.72. For the 12 sets of data used to find u, u has a standard deviation of 0.160. (Note: since w is close to 1, it might seem desirable to assume $w = 1$ and determine by linear regression a revised value of v. When this is done, however, the correlation coefficient drops to 0.64. Since it is considered more important to maintain as high a correlation as possible, the original value of $w = 1.022$ is maintained in subsequent calculations.)

To utilize the results of the Calumet Harbor study for other dredging sites, it is assumed that the concentration dependence upon V_s/V_i and V_t/V_i exhibited by Equation 1 at the Calumet Harbor site is valid for all cutterhead dredging, irrespective of the site or cutting mode. On the other hand, physical and dimensional reasoning suggests that the magnitude of the coefficient u will likely vary from site to site because of such factors as the type of cutting, the size of the cutterhead, the characteristics of the bottom sediments, and possibly the depth of water above the cutterhead. To reflect this possible variation in u, Equation 1 is restated as

$$C/(\rho \times 10^{-6}) = F(V_s/V_i)^v \ (V_t/V_i)^w \qquad (2)$$

in which

$$F = F_F \ F_D \qquad (3)$$

F_F and F_D are full-cut and nonfull-cut dredging parameters, respectively, defined such that

$$u = \log_{10}(F) = \log_{10}(F_F) + \log_{10}(F_D) \tag{4a}$$

$$F_D = 1, \textit{ for full-cut dredging} \tag{4b}$$

$$F_D > 1, \textit{ for nonfull-cut dredging} \tag{4c}$$

and such that F_F is independent of the type of cutting being used. Thus F_D is a factor that accounts for the type of dredging, while F_F is a factor that accounts for dredging effects other than those arising from variations in the type of cutting.

Development of dredging parameter F_F and F_D

At a particular dredging site with only full-cut dredging, such as the James River or the Calumet Harbor dredging site, $F_D = 1$ and F_F is some constant. Furthermore, since the analysis of the Calumet Harbor data isolated the dependence of V_s, V_t, and V_i and this dependence is assumed to exist for other cutterhead dredging sites, the parameter F_F cannot involve a dependence upon the kinematic parameters V_s, V_t, and V_i. A dependence upon these parameters could exist in the parameter F_D, but it is assumed that it does not. Consequently, F_F must depend upon nonkinematic parameters.

Dimensional reasoning suggests that F_F should be a function of various dimensionless groups quantifying the geometric differences between cutterhead dredging at those sites with full-cut dredging. The only readily quantified differences at the two sites for which full cuts were used, i.e, the Calumet Harbor and James River sites, that seem pertinent to the resuspended sediment concentrations in the immediate vicinity of the cutterhead are the characteristic cutterhead size L (Table 3) and the median grain diameter d of the dredged sediments (Table 1). The depth of overlying water might be important in cases of very shallow depth where the cutterhead size and water depth are of similar size, but for the Calumet Harbor and the James River sites the water depths were several times larger than the cutterhead diameter. Such depths would not seem physically significant in influencing the resuspended sediment concentrations in the immediate vicinity of the cutterhead. Thus the only quantifiable dimensionless parameter upon which the dredging factor F_F can depend is the parameter L/d; therefore

$$F_F = f(L/d) \tag{5}$$

Values of L/d are listed in Table 4.

F_D may also have a dependence upon L/d. However, since only the Savannah River site had nonfull-cut dredging and L/d is a constant for a particular dredging site, such dependence cannot be identified even if it exists. The only dependence that might be identified is that which characterizes the differences between types of cutting modes.

The identification of the dependence of F_F upon L/d and of F_D upon the type of cut would ideally be determined by simultaneous use of data from all three cutterhead sites. However, this is not possible since the Calumet Harbor and James River dredging were full-cut operations while the dredging at the Savannah River site used buried and partial cutting but no full cutting. Thus to identify, at least approximately, the dependence of F_F and F_D upon L/d and the type of cut, respectively, it is necessary to decompose the identification process into an examination of the effects of nonfull cuts and an examination of the effects of L/d.

Effects of cutterhead and sediment size

A representative value of F for a particular site and dredge type can be determined by computing the mean value of u and setting F equal to the antilog of this mean value. That is, a representative value of F is the geometric mean of the individual values of F for the same dredge type at a particular site. To make this computation while preserving the dependence of concentration on V_s/V_i and V_t/V_i evidenced in Equation 1, u is defined by

$$u = \log_{10} [C/(\rho \times 10^{-6})] - v \log_{10} (V_s/V_i) - w \log_{10} (V_t/V_i) \quad (6)$$

and computed from the various data for resuspended sediment concentrations for each dredge type at each site using the values of v and w found for the Calumet Harbor site (Table 4). An average value of u is then computed for each type of dredging at each site. The values of u and their standard deviations found at the James River and the Savannah River sites are summarized in Table 4 as are the values of F corresponding to these mean u. The larger variation in u implied by the larger standard deviations at the James River and Savannah River sites (in comparison to that for the Calumet Harbor site) is considered indicative of the more controlled conditions under which the study at the Calumet Harbor site was conducted.

Since, furthermore, the Calumet Harbor and James River studies used full-cut dredging, the values of F for these two sites can be used to preliminarily identify a dependence of F_F upon dredge and sediment size as embodied in the parameter L/d since $F = F_F$ for full cuts; the effects of partial or buried cutting are used, as described below, to refine this preliminarily identified dependence.

The values of L/d and F_F for the Calumet Harbor and James River sites (Table 4) suggest that F_F increases with L/d; such a variation is physically plausible. The larger L/d, the larger the cutterhead size in comparison to the sediments being dredged and the more resuspension that might be expected; the larger F_F, the higher the resuspended sediment concentration. However, since the Calumet Harbor and the James River sites provide only two data points to define this variation, little more can be said about this variation. Consequently, the Savannah River data for partial and buried cutting are needed to further refine this variation. To accomplish this, it is useful to attempt to quantify the effects that partial and buried cuts have on full cutting as suggested by the Savannah River data.

Effects of type of cut

As previously discussed, it is expected that buried- or partial-cut dredging will increase the resuspended sediment concentrations above those for full-cut dredging. This increase in resuspended sediment concentration due to nonfull cutting is formally described by the parameter F_D, where

$$F_D = f\,(P;\ D_m/D_{ch}) \tag{7}$$

where

P = degree of cutterhead penetration for a partial cut

D_m = depth of cut for buried cutting

D_{ch} = maximum diameter of the cutterhead

thus D_m/D_{ch} is the relative depth of cutterhead burial in a buried cut. Precise definitions of P and D_m/D_{ch} are provided below. Other factors may affect F_D, but P and D_m/D_{ch} are the only readily quantified factors distinguishing the types of cuts at the Savannah River site, the only site with nonfull cuts; thus F_D is presumed to depend only on these parameters.

In partial-cut dredging, the increase in resuspended sediment concentration is viewed as the result of the increased sediment washoff from more exposure of the cutterhead blades (in comparison to that for full-cut dredging). In general for a partial cut, as illustrated in Figure 1, the cutterhead will penetrate a vertical distance d_f below the original mudline. The value of d_f assumes a maximum at the point where the partial cut becomes a full cut; at this point $d_f = D_f$. Because the cutterhead shape is approximated as a semi-ellipsoid with maximum diameter D_{ch} and length L_{ch}, D_f can be approximated as (Appendix C)

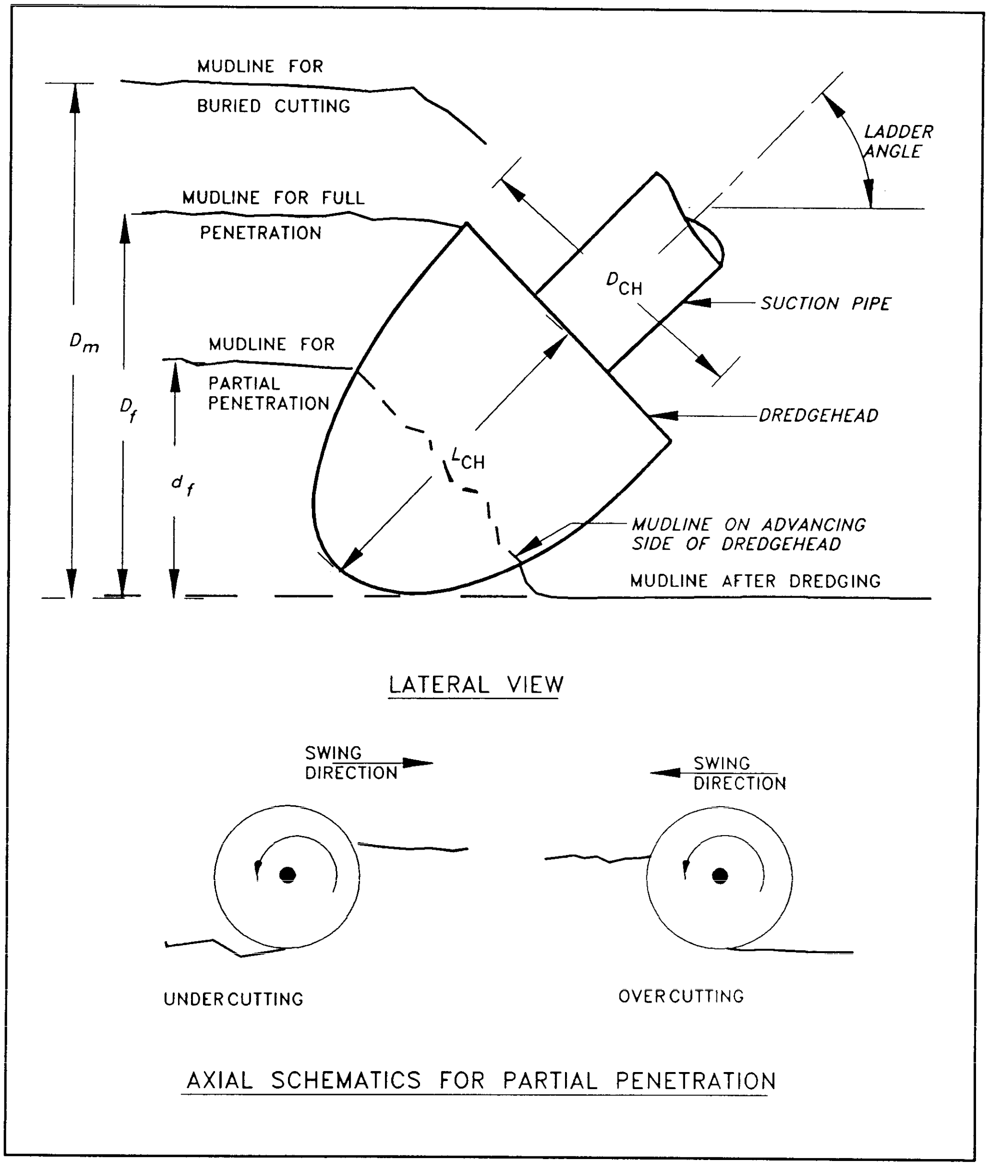


Figure 1. Schematics of cutterhead burial for various types of cuts

$$D_f = (D_{ch}/2) \cos \theta \ (1 + 1/q') \tag{8a}$$

in which

$$1/q' = \left[1 + (2 \tan \theta \ L_{ch}/D_{ch})^2\right]^{1/2} \tag{8b}$$

where θ is the angle the ladder arm supporting the cutterhead makes with the horizontal and q' is the dimensionless y distance to point of tangency of cutterhead ellipse with penetration line. The relative penetration P is then given by

$$P = d_f/D_f \tag{9}$$

where P will obtain a maximum of 1 for a full cut.

The primary mechanism for producing increased resuspended sediment concentrations in buried cutting is not viewed, however, as one of washoff. Rather, it is viewed as the result of bank sloughing and cave-in around the cutterhead. In buried cutting the cutterhead is positioned so that the bottom of the cutterhead is a distance D_m below the mudline, where $D_m > D_f$ (Figure 1). The cutting and removal of bottom sediment material by the cutterhead cause sediments above the cutterhead to fall and slough into and around the cutterhead. These falling and sloughing materials overload the dredge suction capabilities and allow sediments to remain in the waters about the cutterhead, thereby increasing the resuspended sediment concentration levels. These effects are expected to increase as the dimensionless burial parameter D_m/D_{ch} becomes larger.

Since the resuspension increases for depths of cutterhead submergence in the bottom sediments both larger and smaller than D_f, it is convenient to define the dimensionless cutterhead submergence depth D by

$$D = P \qquad \textit{where} \qquad 0 \leq P \leq 1 \tag{10a}$$

for partial cuts and

$$D = D_m/D_f \qquad \textit{where} \qquad D_m \geq D_f \tag{10b}$$

for buried cuts. Thus,

$$F_D(P;\ D_m/D_{ch}) = F_D(D) \qquad \textit{and} \qquad D \geq 0 \tag{11}$$

and since $F_F = f(L/d)$ and $F = F_F F_D$

$$F = f(L/d;\ D). \tag{12}$$

Note that F is undefined for $D < 0$.

F_D is assumed to have the general form

$$F_D = 1 + (F_D)_w + (F_D)_b \tag{13}$$

in which $(F_D)_w$ is the resuspension function describing the effects of sediment washoff from the cutterhead blades for partial cuts and $(F_D)_b$ is the resuspension function describing the effects of bank sloughing and cave-in on resuspension for buried cuts. The general characteristics expected and therefore proposed for $(F_D)_w$ and $(F_D)_b$ are

$$(F_D)_w = 0 \qquad \textit{for} \qquad D \geq 1 \tag{14a}$$

$$(F_D)_w > 0 \qquad \textit{for} \qquad 0 < D < 1 \tag{14b}$$

$$(F_D)_b = 0 \qquad \textit{for} \qquad D \leq 1 \tag{14c}$$

and

$$(F_D)_b(D > 1) > (F_D)_b(D = 1) \tag{14d}$$

Also, $(F_D)_w$ decreases monotonically with increases in D for $0 \leq D \leq 1$ and $(F_D)_b$ increases monotonically with increasing D for $D > 1$. $(F_D)_w$ and $(F_D)_b$ are undefined for $D < 0$. Also note that for a full cut (i.e., $D = 1$), $(F_D)_w = (F_D)_b = 0$; therefore Equations 13 and 14 imply that when $D = 1$ (full-cut dredging)

$$F_D = 1 + 0 + 0 = 1 \tag{15}$$

The constraints of Equations 14 and 15 on F_D can be examined in light of the data for the Savannah River site. For this site, the penetration depth d_f for the cutterhead in partial cut operations was in the range of 1 to 3 ft, while the ladder angle θ was approximately 45 deg. Thus, using Equations 8, 9, and 10, D_f = 6.24 ft and D was therefore in the range of 0.1 to 0.5. Since the average u for the partial cuts at the Savannah River site is -0.556, $F = F_F F_D$ is computed to be 0.278; thus

$$F/F_F = F_D = 1 + (F_D)_w + (F_D)_b = 1 + (F_D)_w + 0 = 0.278/F_F \quad (16)$$

or

$$(F_D)_w = 0.278/F_F - 1 \quad (17)$$

for D in the range of 0.1 to 0.5.

For buried cuts at the Savannah River site, the cutterhead was buried to a depth of approximately 20 ft. Thus $D = D_m/D_f$ = 20 ft/4.93 ft = 3.2. Since the average u for the buried cuts at the Savannah River site is 1.229, F = 16.94. Thus, in a manner similar to that for the partial cuts,

$$(F_D)_b = 16.94/F_F - 1 \quad (18)$$

for D approximately 3.2.

Actual values of $(F_D)_w$ and $(F_D)_b$ for the two cutting modes at the Savannah River site require an estimate of F_F for the Savannah River site. This estimate is provided in the following section.

Full-cut dredging function

The full-cut dredging parameter, F_F, has been deduced previously to be a function of *L/d*; two values for this function have been identified using the data from the Calumet Harbor and the James River sites (Table 5). Estimates of F_F for the Savannah River site can be provided by (a) an examination of the potential range for F_F and (b) a physically based model for partial-cut dredging. Estimates using both these techniques are provided below. These estimates then allow an approximation to F_F as a function of *L/d* to be deduced.

Fortuitously, *L/d* for the Savannah River site is intermediate between the *L/d*'s for the Calumet Harbor and the James River sites. Since F_F (which equals F for full cuts) is physically expected to increase with increasing *L/d*, F_F at the Savannah River site must be greater than the F_F at the Calumet Harbor site and less than the F_F at the James River site; i.e.,

$$F_F(L/d = 27{,}928) < F_F(L/d = 94223) < F_F(L/d) = 123{,}680 \quad (19)$$

Therefore, using the data of Table 4

$$0.0892 < F_F(L/d = 94{,}223) < 82.1 \quad (20)$$

In addition, since $F = F_F F_D > 1$ for nonfull cuts, the buried-cut results for the Savannah River site require that

$$F_F < 16.94 \quad (21)$$

while the partial-cut results for the Savannah River site indicate the more restrictive condition

$$F_F < 0.278 \quad (22)$$

Combining these limits yields the condition

$$0.0892 < F_F(L/d = 94{,}223) < 0.278 \quad (23)$$

which is illustrated in Figure 2.

The discrete points for F_F provided by the Calumet Harbor and the James River sites plus the range of values for F_F provided by the Savannah River site provide a means to estimate a continuous function for F_F; such a function is illustrated in Figure 2. A precise equation for this function is developed below. However, this equation must be applied cautiously because of the limited data used in its development.

To provide an estimate of a specific value of F_F for the Savannah River site, a physically based model for $(F_D)_w$ can be formulated. It is recognized that such a model will be unverified; however, this model does provide not only a physically reasonable value for $(F_D)_w$ but a value of F_F that is also consistent with the previously defined limits on F_F.

In a partial-cut operation, the increase in resuspended sediment concentration is viewed, as previously discussed, as the result of increased cutterhead surface area available for sediment washoff. The area over which the sediment washoff occurs is taken as the exposed cutterhead surface area not

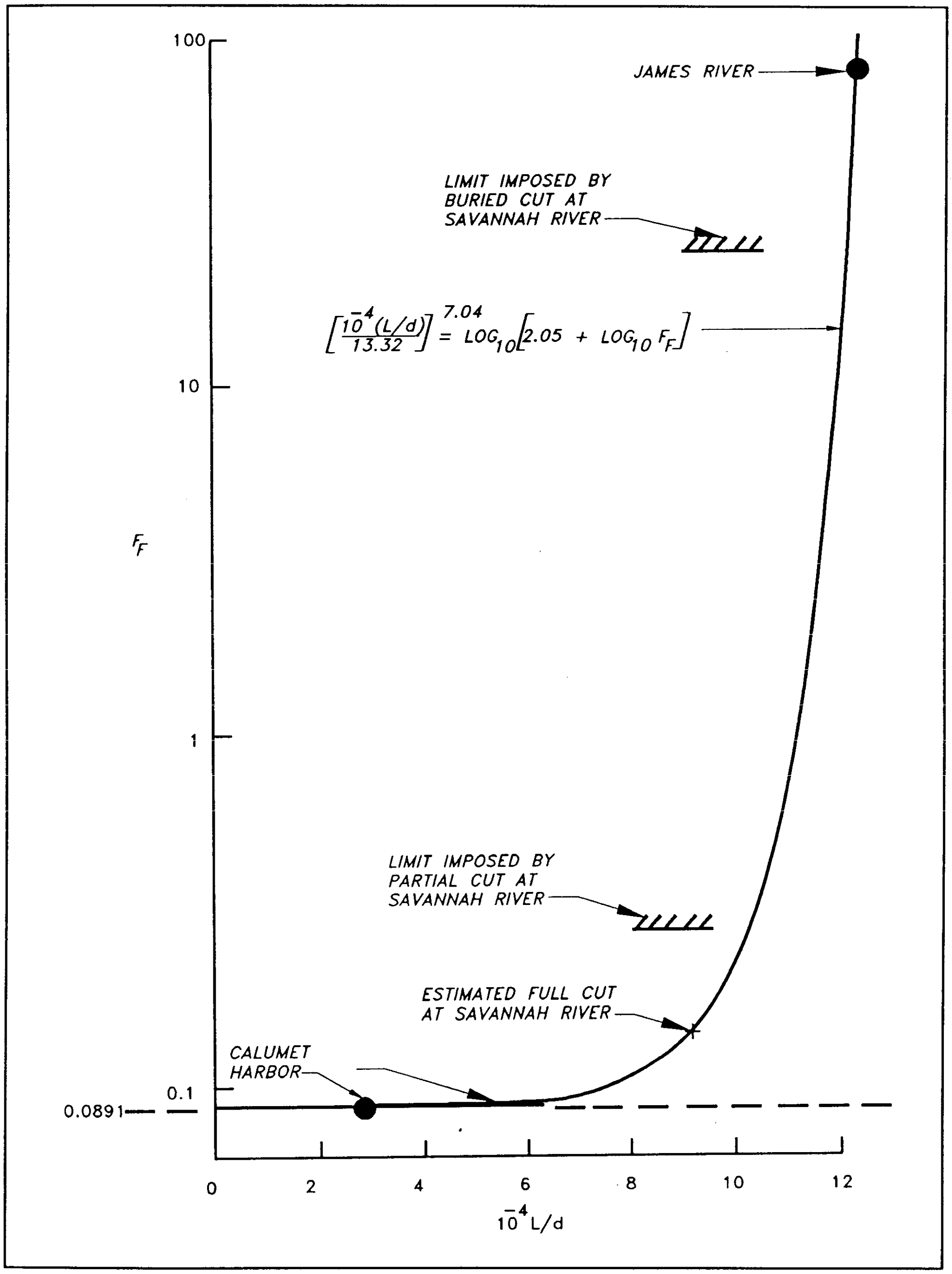


Figure 2. Full-cut dredging function F_f for cutterhead dredge

submerged in the bottom sediments being dredged. This exposed area is a fraction of the source volume surface available for sediment generation $F_c < 1$ of the total cutterhead surface area, A_{ch}. The area exposed on the side of the cutterhead advancing into the sediments (i.e., swinging into the sediments) is different from that on the opposite, nonadvancing side of the cutterhead, as illustrated in Figure 1. Let the fraction of surface area exposed on the advancing side of the cutterhead be F_a and the fraction on the nonadvancing side be F_n , where

$$F_c = F_a + F_n \tag{24}$$

and $F_a \leq F_n$, $F_a \leq 0.5$, and $F_n \leq 0.5$. The fraction of nonexposed submerged surface areas on each side of the cutterhead is therefore, in general, 0.5 - F_a and 0.5 - F_n . On the nonadvancing side of the cutterhead it is assumed, however, that the entire cutterhead surface is exposed, and thus $F_n = 0.5$. On the advancing side of the cutterhead, the bottom sediments are assumed to extend a vertical height d_f above the low point of the cutterhead and slope downward across the cutterhead perpendicular to the axis of cutterhead rotation as shown in Figure 1. As a consequence 0.5 - F_a is

$$0.5 - F_a = 0.5\ a_z \tag{25}$$

in which, as detailed in Appendix C and by replacing P with D in accord with Equation 10a, a_z, the fraction of cutterhead semi-ellipsoid surface submerged below mudline, is approximated by

$$az = 1 - \left[1 - \left(2_{y_p}/D_{ch}\right)^2\right]^{1/2} \qquad for \qquad D \geq P_o \tag{26a}$$

and

$$a_z = 0 \qquad for \qquad D < P_o \tag{26b}$$

in which

$$2_{y_p}/D_{ch} = q'\ [D(q' + 1) - 1] + \left((1 - q'2)\right.$$
$$\left.\{1 - [D\ (q' + 1) - 1]^2\}\right)^{1/2} \tag{26c}$$

$$P_o = [1/(1 + q')] - [(1 - q')/(1 + q')]^{1/2} \tag{26d}$$

Thus, considering both sides of the cutterhead it follows that

$$F_c = 1 - 0.5\ a_z \qquad (27)$$

If the increase in resuspended sediment concentration from partial cutting is presumed to be proportional to the increase in exposed surface in a partial cut,

$$(F_D)_w = F_c/F_{c(D=1)} - 1 = 1 - az \qquad (28)$$

Applying the model of Equations 24 through 28 to the Savannah River data, the following is obtained for θ = 45 deg, D = 0.3 (the average of the range of 0.1 to 0.5 identified above), and D_f = 6.24 ft as previously determined: q' = 0.5145, P_o = 0.094, $2_{yp}/D_{ch}$ = 0.4378, az = 0.101, F_c = 0.950, $(F_D)_w$ = 0.899, and F_D = 1.899. These values of F_D and $(F_D)_w$ are physically realistic.

Furthermore, if F_D = 1.899, it follows from Equation 3 and the data of Table 4 that for the Savannah River data $F_F = F/F_D$ = 0.278/1.899 = 0.1464 ≈ 0.15. This value for F_F falls nicely within the bounds identified for F_F. Thus the above-described model for $(F_D)_w$ appears to be reasonable.

If a value of F_F = 0.15 is accepted as an estimate for F_F for the Savannah River data, an empirical curve can be fitted to the three data points for F_F now provided by the Calumet Harbor, the Savannah River, and the James River data. With only three data points, the data are closely fitted by the equation

$$[(10^{-4}\ L/d)/13.3]^{7.04} = \log_{10}[\log_{10}(F_F) + 2.05] \qquad (29a)$$

or equivalently

$$\log_{10}(F_F) = 10^{[10^{-4}(L/d)/13.32]^{7.04}} - 2.05 \qquad (29b)$$

With F_F now estimated to be 0.15, Equation 18 can be used to determine that $(F_D)_b$ = 111.9. The values of $(F_D)_w = F_D$ = 0.899 for D = 0.3 and $(F_D)_b = F_D$ = 111.9 for D = 3.2 along with F_D = 0 for D = 1 allow an approximate functional form for F_D to be identified, as shown by the curve in Figure 3. The empirical curve of Figure 3 is given by the equation

$$F_D = 1.9039(D - 1)^2 + 0.4116(D - 1)^7 \qquad (30)$$

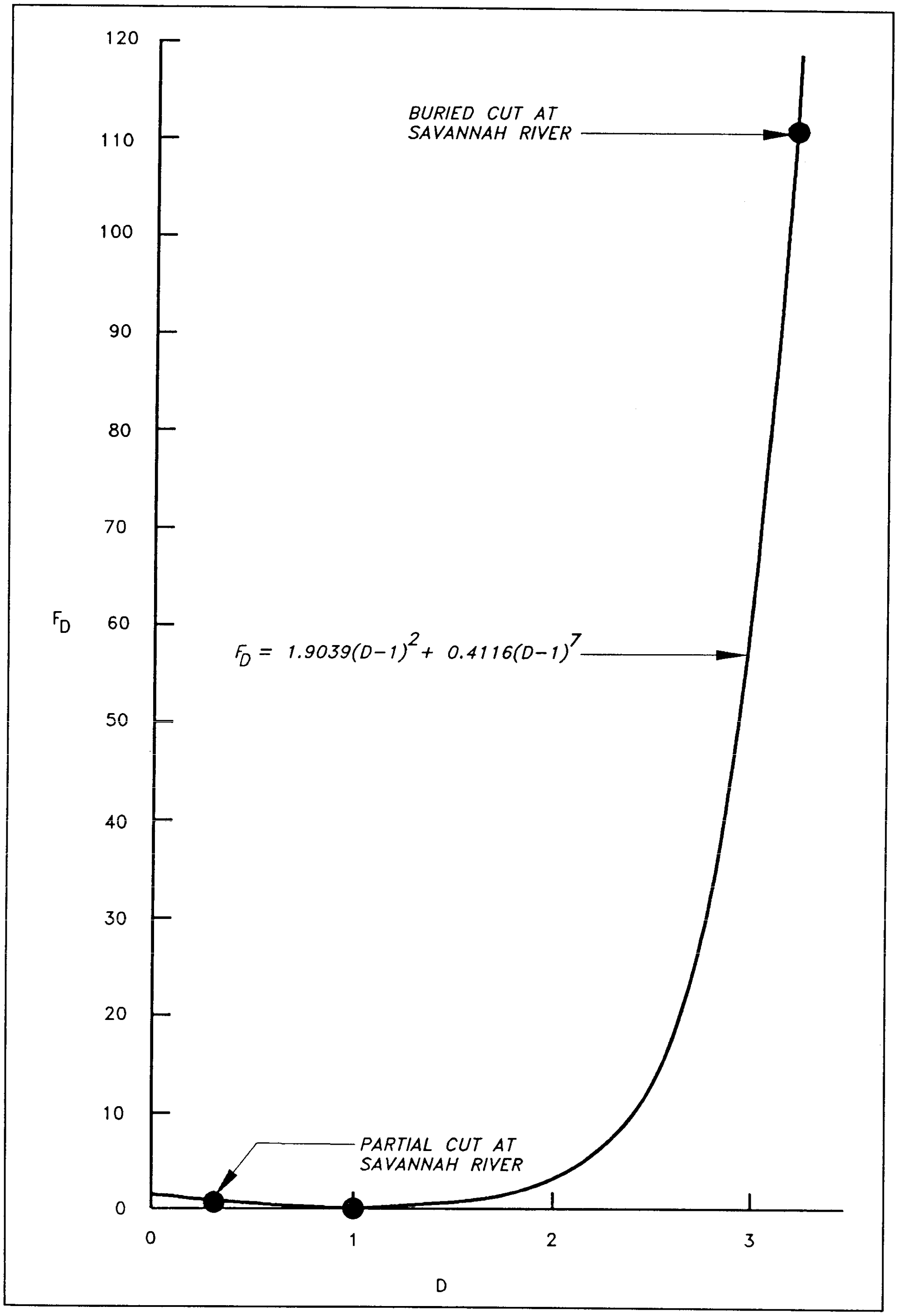


Figure 3. Cutterhead cutting type function F_D

Equations 29 and 30 illustrate the general relationships between important dredging and sediment parameters but should be applied cautiously to other dredging sites. However, the use of these equations must be tempered considerably by the limited data upon which they are based and their mathematical characteristics. Values of F_F generated using Equation 29b increase dramatically with small changes in the median grain diameter d. Similarly, Equation 30 responds dramatically to values of D in excess of 2. Consequently, these equations can predict large variations in predicted suspended sediment concentrations with small changes in these variables.

General data correlation

With an estimated value of F_D for the Savannah River data provided by Equation 30 it is possible to infer what the resuspended sediment concentrations at the Savannah River site would presumably have been if a full cut had been used but all other factors had remained the same. If the Savannah River data are adjusted to reflect full-cut dredging, then collectively the Calumet Harbor, the James River, and the adjusted Savannah River data provide a combined set of data to assess the ability of the full-cut model to generally describe the resuspended sediment concentrations induced by a cutterhead dredge.

To adjust the Savannah River data, all partial-cut concentrations are reduced by the factor $1 + (F_D)_w = 1.899$; all buried cut concentrations are reduced by the factor $1 + (F_D)_b = 112.9$. The F_F factor for the resulting data is 0.15, as computed above, from which $u = -0.824$ is determined (Table 4). These resulting data, along with the appropriate V_s, V_t, and V_i, are combined with the Calumet Harbor data (with $F_F = 0.0892$) and the James River data (with $F_F = 87.3$), each with their various V_s, V_t, and V_i values, to provide a general data set against which Equation 2, for a full cut, can be tested.

The observed resuspended concentrations (or, in the case of the Savannah River data, the adjusted concentrations) are plotted against the concentrations predicted by Equation 2 in Figure 4. The straight line through the data indicates the line of perfect fit. The degree of scatter about this line of perfect fit can be quantified by computing the correlation coefficient r^2 and the standard error in estimate between the computed and observed data, treating the predicted values of the logarithm of concentration as the independent variable and the observed values of the logarithm of concentration as the dependent variable in a simple linear regression. Computed correlation coefficients and standard errors of estimate for the logarithms of the concentrations are listed in Table 5 for all the data and various subsets of the data. The overall correlation coefficient r^2 for the entire data set is 0.556. Subsets of the complete data set produce differing levels of correlation as listed in Table 5. The highest degree of correlation ($r^2 = 0.724$) was obtained for the Calumet Harbor data; as discussed earlier, the Calumet Harbor study was a more controlled field study. The lowest correlation, nearly zero, was obtained for the James River data. This low correlation is believed to arise because of the necessary use of only average swing velocities in the computation of the V_s/V_i and V_t/V_i parameters. Reported data for the study did not distinguish between varying swing speeds during the course of the dredging operations, and it is

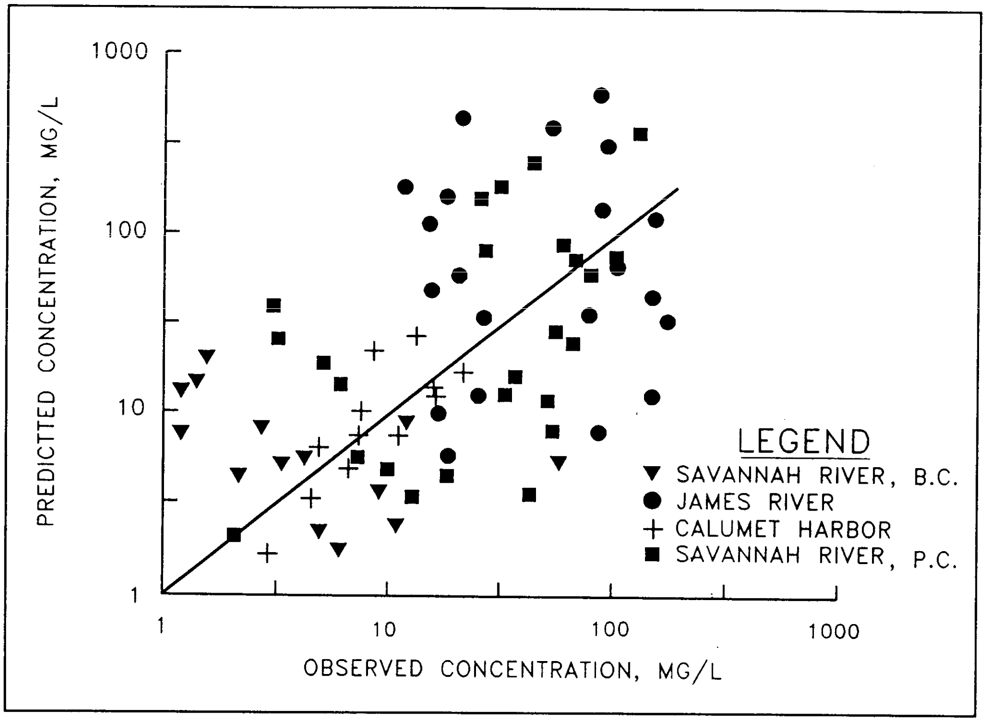


Figure 4. Sediment resuspension predictions for cutterhead dredge operating at full-cut burial

believed that there was, in fact, considerable variation. The overall correlation is dominated by the Savannah River data because of the relatively larger number of data items for the Savannah River study.

While there is far from perfect agreement between the predicted and observed data in Figure 4, there is a sufficiently reasonable comparison, it is believed, to conclude that the model provided by Equations 2, 3, and 4 as well as the full- and partial-cut models as described above provide a reasonable approach for estimating resuspended sediment concentrations produced by hydraulic cutterhead dredging. However, the equations should be applied cautiously to sites different from those used to develop the relationships. As more data become available in the future to further test this mathematical model, modifications to this exploratory model will certainly be necessary.

Dustpan Dredge

The dustpan dredge, used at the James River study site, was proposed as a means of reducing levels of resuspended sediments. This dredge, in the modified form used at the James River site, merely sucked up sediment loosened by the forward advance of the dredge, apparently creating a bulldozerlike motion to scoop and push sediment into the dredgehead where it would be sucked upward by the suction velocity. Winglets on each side of the dredgehead were supposed to restrict dispersal of sediment into surrounding waters.

Although limited data prevent a detailed evaluation of the dustpan dredgehead behavior, near field measurements (summarized in Appendix E) indicated resuspension was as high as or higher than that produced by the cutterhead dredge (Vann[1] 1983; Havis 1988; Raymond 1982; McLellan et al. 1989). Some of this may have been due to the apparently substantially larger forward velocities used with the dustpan dredge in comparison to the estimated swing velocities used for the cutterhead dredge (see Appendices E and F). In addition, if the effective area over which the intake suction velocity to the dredge occurs is approximated as a quadrant of a cylinder with a 2-ft radius and 28-ft length (Table 2), the effective surface area of the dredgehead is about 88 percent of that for the cutterhead dredge head used at the James River site. On the other hand, data presented by Vann[1] on dredge production during the testing period suggest that suction discharges of the dustpan dredge were approximately 60 percent of those for the cutterhead dredge. Thus the dustpan dredge may have had effective suction intake velocities of about $0.60/0.88 = 0.68 = 68$ percent of those of the cutterhead dredge. Since the cutterhead correlation suggests concentration levels are strongly inversely proportional to intake velocity, the larger concentrations observed during the dustpan dredge operation may be a result, at least in part, of the apparently smaller effective intake suction velocities for the dustpan dredgehead.

Matchbox Dredge

The matchbox dredge, studied at the Calumet Harbor site, was also proposed as a means to reduce release of resuspended sediments to the water column. The matchbox enshrouds the dredge suction intake with a box-type cover that allows sediment passage only through the open sides of the box. The necessary agitation and dislodgement of bottom sediment is accomplished by the mechanical and hydraulic forces as the dredgehead swings back and forth. There are no rotating cutter blades; thus presumably the resuspension of sediments by the dredge operation is insensitive to the direction of swing of the dredge ladder.

The concentration levels measured during three distinct sets of operating conditions for the matchbox dredge at Calumet Harbor (Appendices K and L) indicated that no measurable reductions in resuspended sediments in the immediate vicinity of the dredgehead were achieved compared to the conventional cutterhead dredge. In fact, for comparable operating conditions, sediment concentrations were sometimes greater than those for the cutterhead suction dredge. Previous researchers (Hayes, McLellan, and Truitt 1988; McLellan

---

[1] R. G. Vann. (undated). "James River, Virginia dredging demonstration in contaminated material (kepone), dustpan versus cutterhead," Report, U.S. Army Engineer District, Norfolk, Norfolk, VA.

et al. 1989) concluded that operator inexperience with this type of dredge, lack of adequate control in matchbox positioning near the channel bottom, and frequent clogging of the suction line affected the performance of the matchbox dredge.

The importance of proper positioning of the dredge near the channel bottom is emphasized by the results for the cutterhead suction dredge found above. While it is not immediately apparent how the absence of cutterhead rotation speed could be accounted for in describing resuspension with Equation 2, the presence of the ratio of swing speed to intake suction velocity raised to a 2.8 power suggests considerable sensitivity to the effective suction velocity in the water immediately surrounding the matchbox. Consequently, the effectiveness of the matchbox dredge may be very dependent upon the ability to precisely control the position of the matchbox near the bottom and achieve and maintain effective suction velocities conducive to small resuspension.

Hopper Dredges

One dredging study with a hopper dredge was conducted under the IOMT program (Table 1). Sediment resuspension was measured during both nonoverflow and overflow conditions in Grays Harbor, Washington. Because only one study has been accomplished for a hopper dredge, little quantitative information can be extrapolated as to the magnitude of sediment sources that might be generally produced by a hopper dredge. However, some observations are worthy of note.

Nonoverflow operating mode

Hopper dredges, because they are often used in strong current areas typical of many estuaries and outer harbors, use a hydraulic draghead on a dragarm suspended beneath the hopper vessel to cut and draw sediment upward into the ship's hoppers. The forward motion of the ship provides the primary cutting force while the hydraulic suction provides the necessary hydraulic lift and transport.

The actual suspended sediment concentrations aft of the moving hopper dredge studied in the IOMT program at Grays Harbor, Washington, are shown in Figure 5 (see Appendix N for concentration data listing). As an aid to viewing the data in Figure 5, approximating smooth curves have been drawn through each of the two data sets displayed in the figure. These data are vertical average concentrations within the estimated plume boundaries aft of the moving ship and have been averaged over longitudinal segments to provide a smooth plot of sediment concentration with distance as an aid for extrapolation. Strong tidal currents and ship movement prevented sampling in the immediate vicinity of the ship, and sediment concentrations at distances

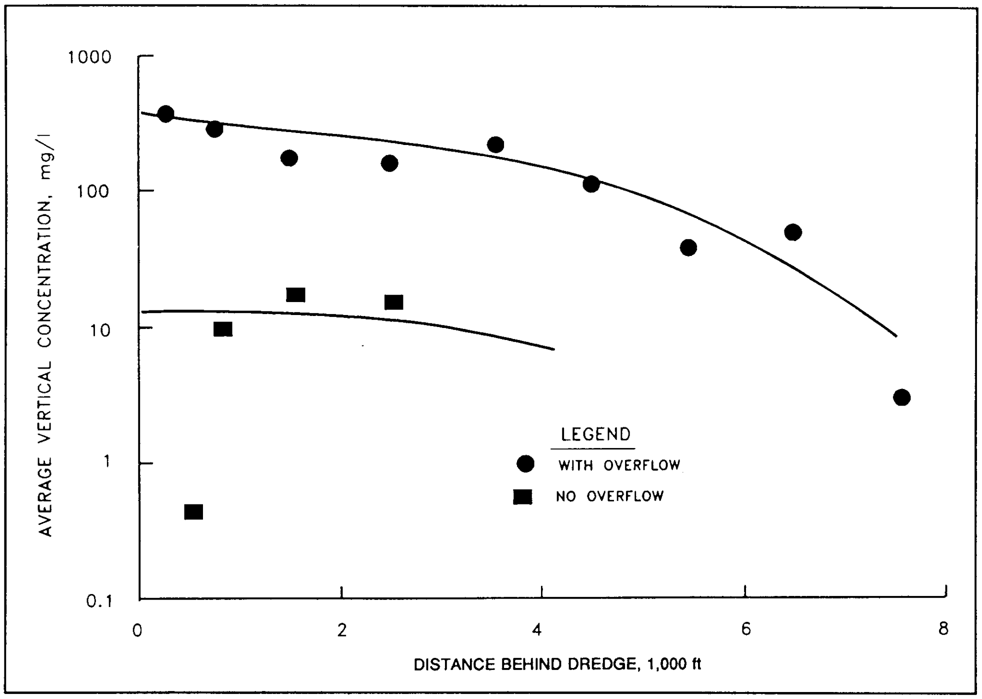


Figure 5. Resuspended sediment concentrations observed behind a hopper dredge operating in Grays Harbor, Washington

very close to the ship can only be estimated by extrapolation of data from greater distances.

Figure 5 shows that, as would be expected, the sediment concentration generally decreases with increasing distance from the dredge. The drop-off in sediment levels are evidenced in Figure 5 at a short distance downstream of the dredge in its nonoverflow operating mode. This is believed to be result of a combination of localized distortion of the sediment plume due to the ship's motion and associated large-scale turbulence and the difficulties in sampling along the axis of the plume in the regions nearer the dredge ship. If this lower value some 500 ft distant from the dredge is disregarded, the vertical average sediment concentration at zero distance from the dredge is estimated by extrapolation to be only about 13 mg/ℓ. However, this 13 mg/ℓ represents a vertical average. If the sediment throughout the vertical extent of the water column is presumed to be concentrated in a zone of height equal to the approximate size of the dredgehead (Table 2), the source concentration for the dredgehead becomes equal to approximately 146 mg/ℓ, as listed in Table 3.

Overflow operating mode

A distinctive feature of hopper dredges as sources of suspended sediment arises from the possibility that a hopper dredge normally provides two sources of sediment. Hopper dredges may be operated in either an overflow or non-overflow mode. In the nonoverflow mode, the material dredged from the channel bottom is loaded into the ship's hoppers only until the hoppers are full, after which the sediments are transported to their disposal site. Sediment levels above background levels are generated only by the disturbance of the moving dredge ship and its propellers, the draghead being towed by the dredge along the channel bottom, and increased velocities created by the waters being siphoned upward through the draghead. The source of suspended sediments is thus the agitation of sediments on the channel bottom by the dredge and dredge ship.

In the overflow mode of operation, the hoppers are filled beyond their point of capacity so that intentional spillage occurs. By pumping past the point of overflow, greater density is achieved in the sediment-laden waters retained in the hoppers; the greater density increases the effective capacity of the dredge with a resulting increase in the economy of the dredging operation. The supernatant overflow waters from the hoppers are discharged to the near-surface waters around the dredge ship, providing a second, near-surface source of suspended sediments from the dredging operation. As might be expected because of the high flow and concentration of sediments in the waters siphoned from the channel bottom and their short retention time in the hoppers, hopper overflow produces higher suspended sediment concentrations than the dredging action itself (McLellan et al. 1989).

The effects of these two different sources of sediment in a hopper dredging operation is illustrated by the data of Figure 5. It is apparent that vertical average sediment concentrations with overflow are approximately one to two orders of magnitude larger than without overflow in the regions near and at moderate distances downstream of the dredge. Generally, the average concentration, due to both dispersion of the sediment plume and settling of suspended particles, decreases with downstream position. The vertical average concentration level for the overflow mode of operation at a zero distance from the dredge is, by extrapolation, about 355 mg/ℓ.

Clamshell Dredges

Factors influencing resuspended sediment levels

A variety of factors in the use of clamshell dredges have been identified or suggested as contributing to the resuspension of sediment. Previous investigators (e.g., Hayes, McLellan, and Truitt 1988) have suggested that bucket impact, penetration, and withdrawal are major contributors to sediment resuspension. An additional source of sediment in the near field water column is the loss of sediment from the clamshell bucket as it rises through the water column, breaks the water surface, and is swung across to the point of bucket opening and dredged material release. In its upward movement, sediments overflow the top of the bucket, leak from the sides and bottom of the bucket, and are washed from the sides of the bucket. Based upon these factors, a general equation for sediment resuspension during clamshell dredging can be written as:

$$\begin{array}{c} \text{Total} \\ \text{Resuspension} \end{array} = \begin{array}{c} \text{Resuspension by} \\ \text{bucket impact,} \\ \text{penetration, and withdrawal} \end{array} + \begin{array}{c} \text{Resuspension} \\ \text{bucket leakage} \end{array}$$

$$+ \begin{array}{c} \text{Resuspension by} \\ \text{bucket spillage} \end{array} + \begin{array}{c} \text{Resuspension by} \\ \text{washing of sediment} \\ \text{from bucket walls} \end{array}$$

While this equation includes the primary components of resuspension, these components are not easily modeled and are influenced considerably by other dredging characteristics. These characteristics are discussed below.

An important factor influencing total suspended sediment levels in the water column is the bucket cycle time, i.e., the time used to make a complete bucket lift, recovery swing, bucket opening and release, return swing, and bucket drop and return to the channel bottom. Other operational factors that may influence sediment generation include the amount of bottom sweeping or smoothing, if any, with the bucket by the bucket operator, and the number of passes used in removing the sediment at a particular location.

Bucket design and size, as well, can be expected to affect the amount of sediment generated. In the IOMT studies conducted to date, two different types of buckets have been used: (a) an open bucket (which is the common type of clamshell bucket), which allows some free drainage of water and sediment overflow as the bucket is hoisted upward, and (b) a closed bucket (sometimes referred as a watertight bucket). Various types of closed clamshell bucket designs have been previously described[1] (Arctic Laboratories et al. 1985; Herbich and Brahme 1991). The particular design of the closed or watertight clamshell buckets used in the IOMT studies have been described (Raymond 1984; Hayes, McLellan, and Truitt 1988; Hayes 1986b; Montgomery and Raymond 1984). Irrespective of the details of the design or the name given particular designs, these bucket designs are intended to minimize drainage from the bucket.

Sediment resuspension from the operation of a clamshell dredge may also arise from effects not directly associated with the bucket operation. These effects can include scow movement and associated tug operations, scow overflow, and direct release or "sidecasting" of dredged sediments (as was the case at the Lake City site).

---

[1] U.S. Army Corps of Engineers, Office of Civil Works. (n.d.). "Dredging," Engineering School Manual, The Engineering Center, Fort Belvoir, Virginia.

Data analysis

Concentration levels very close to a clamshell dredge could not be measured in the field during actual dredging operations because of the danger posed by a lifting, swinging clamshell bucket. Consequently, in order to obtain a source concentration level for a particular clamshell bucket dredge, concentration levels at various radial distances from the dredge were extrapolated to deduce an approximate concentration at a zero radial position representing the idealized center of the dredge. Appendices P, Q, S, U, W, X, and Y tabulate concentration data for the various clamshell dredge operations.

Several factors had to be considered in developing the concentration data to make this extrapolation. Firstly, it was recognized that there was considerable apparent random scatter in the concentration data because of the inherent difficulties in making field measurements in the various dredge studies. Secondly, because the data at each dredging site were limited, it was necessary that as much of the available data as possible be used to estimate the source concentration at the idealized axis of clamshell bucket rise and fall. To address the first factor, concentration data were vertically averaged over the depth of the water column for each set of measurements at a particular time and location. To address the second concern, temporal variations arising from changing river current patterns were neglected and tidal effects were, as discussed below, only approximately accounted for; the amount of data was insufficient to segregate data by time or fraction of a tidal cycle.

In addition, the far field concentration levels used to make the source concentration estimates are not a function solely of radial distance, but rather depend on both radial distance and angular orientation relative to the dredge and current that may exist. However, because the data were limited, variation of concentration with angular position was difficult to distinguish in the field data at a level of detail considered necessary for making the desired extrapolation to a zero radial distance. Consequently, it was decided that only radial variation of concentration would be used in making the desired extrapolation. Two factors lessen the error that neglect of the angular orientation introduce: (a) the far field data used to make the extrapolation tended to be concentrated in regions along the streamwise axis (either upstream or downstream of the dredge) of the channel and sediment plume produced by the dredging; thus much of the data had approximately similar upstream or downstream angular orientations relative to the dredge; and (b) far field concentration patterns tended to become less dependent on angular orientation the smaller the radial distance from the dredge; thus in the vicinity of the dredge, far field concentration data assumed similar magnitudes for similar radial distances irrespective of angular orientation.

While temporal variations in currents and detailed tidal variations were not accounted for in the far field data analysis, it was clear from both the raw data and studies by previous investigators (Hayes, McLellan, and Truitt 1988; McLellan et al. 1989; Havis 1988) that both the typical river current and tides, when present, produced some asymmetry in the streamwise pattern of the far field concentration patterns. A river current would stretch the time-averaged concentration field surrounding the dredge in the direction of the current flow while compressing it in the opposing direction. Tidal variations, on the other hand, would cause a crudely cyclic variation in the concentration field that would evidence itself as two zones of high concentration when far field concentrations were averaged over time. Both these influences are clearly linked to the streamwise motion of a settling sediment particle and the horizontal distance in an upstream or downstream direction that a particle can move before it finally settles to the channel bottom.

Since the data were sufficient in number only for analysis on a time-averaged basis, the asymmetry in far field concentrations apparently introduced by river current and tides was accounted for by locating all data at adjusted radial positions somewhat different from their actual radial positions. Points upstream of the dredge in sites dominated by river current flow or, in the cases of strong tidal influences, points for measurements taken during the ebb tide had the streamwise component of their radial distances increased by a constant length, while points taken downstream of the dredge or on the flood tide had the streamwise component of their radial distances decreased by a similar amount. The actual adjustment varied with the site and was selected by trial and error to reduce the apparent scatter in vertical average concentration at various radial positions. Because data scatter could not be totally eliminated and reduction in scatter was evaluated subjectively, the selection of the adjustment distance was refined only to 10-ft increments. The magnitude of these adjustments (0 to 100 ft) is physically consistent with the time available for the horizontal movement that a falling sediment particle could undergo moving at current or tidal speeds typical of the various sites (Table 1).

Once the adjusted positions were determined for the concentration data for a particular clamshell dredge, the concentrations were plotted and fitted by eye with a smooth curve. Extrapolation of the curve to a zero radial distance yielded the clamshell dredge source concentration. These estimates of observed source concentrations are listed in Table 3. To reduce the effects of random error and angular orientation at larger radial distances in the plotting and curve fitting, the vertical average concentrations at different adjusted radial positions were averaged over radial zones before plotting. The width of the averaging zone depended on both the study site and the radial distance because of the differences in the number of data at different radial distances in each data set.

Figure 6 shows the radial variations of concentrations for the five different open clamshell bucket dredge studies (Table 1). For clarity, the concentrations have been normalized by the estimated source concentrations. Also for the sake of clarity, the closed clamshell data are not plotted in Figure 6; however, they behave in the same general manner as the open-bucket clamshell data shown. While there is certainly considerable scatter, the data shown in Figure 6 for each of the various sites do demonstrate a crude exponential decay of concentration with adjusted distance. Note that the approximate rate

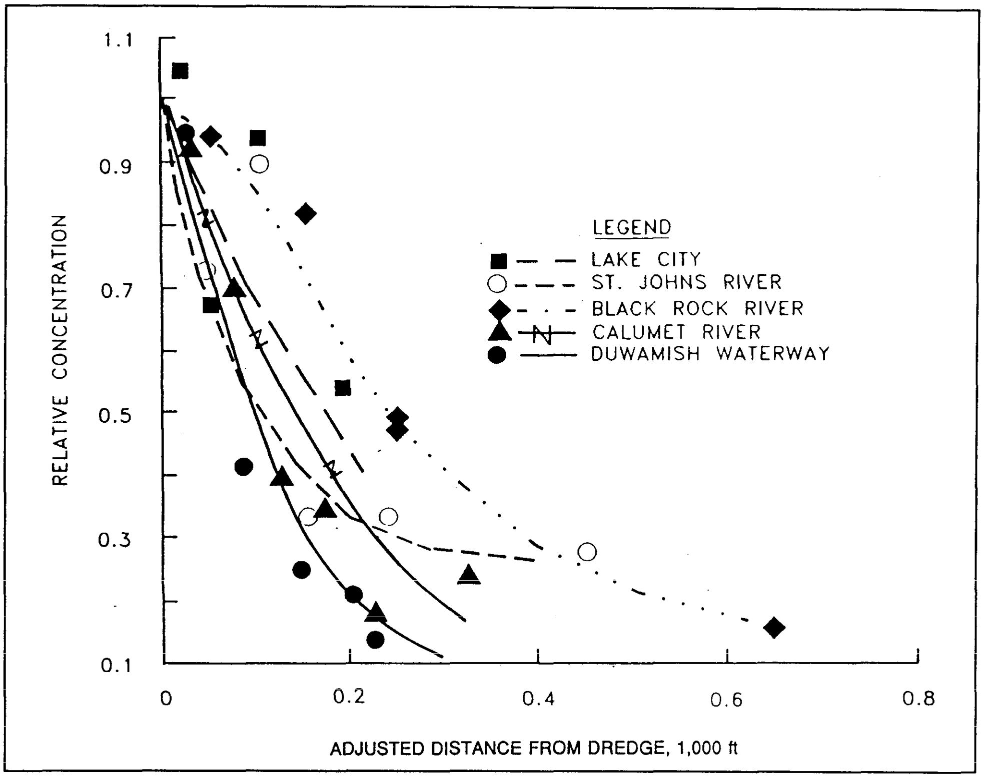


Figure 6. Relative resuspended sediment concentration versus distance for open-bucket clamshell dredges

of decay is different for each dredge. The decay is also different for each type of clamshell (i.e., open or closed). Such differences are to be expected because of differing sediment and flow characteristics.

Open clamshell source concentrations

The clamshell dredge source concentrations determined for the various dredges show differences from one another, as would be expected. These differences arise because of differences in sediment characteristics, clamshell bucket features, and bucket operation; their influence of these factors can be quantified through a combination of physical and dimensional reasoning. Less well-defined background flow conditions and local site peculiarities might also influence these source concentrations, but cannot be identified in the present analysis.

If dimensional reasoning is applied, one recognizes that the bucket size compared to the dredging depth should be important to the levels of sediment produced by a clamshell bucket: the bigger the bucket compared to the flow depth, the greater the sediment resuspension. Thus the dimensionless parameter B, where

$$B = b/h \tag{31}$$

in which b is a representative size of the clamshell bucket and h is the representative dredging depth (Tables 2 and 3), should influence the source concentration. The shape of a clamshell bucket is crudely square in the horizontal plane and one vertical plane and triangular in the third, orthogonal plane. Thus if the clamshell bucket volume is V_{cb}, then the characteristic size of the bucket can be defined by the relation

$$V_{cb} = b^3/2 \tag{32}$$

The time the clamshell resides in the water column should also affect sediment production; the longer the bucket is in the water column, the more time available for sediment loss from the bucket. The time in the water column should be closely proportional to the bucket cycle time for operation by an experienced dredge operator. Counterbalancing this effect, however, is that longer cycle time implies fewer bucket loads being removed in any definite period of time and thus less total sediment being removed over an extended period of time. Cycle times T for the open-bucket clamshell dredges are given in Table 2. This cycle time can be incorporated in a dimensionless parameter by defining a dimensionless cycle time S, where

$$S = v_s T/h \tag{33}$$

in which v_s is a representative settling velocity of the resuspended sediments.

A representative settling velocity v_s can be estimated from Stokes law using the median grain diameter d and specific gravity of the dredged sediments; values of v_s computed from Stokes' law are listed in Table 3 for all the dredge sites except Lake City and St. Johns River. No data on sediment size or settling characteristics were available for the Lake City site, and therefore no settling velocity was estimated. While median grain size data was also not available for the St. Johns River site, one set of settling column measurements for high concentrations of sediments was available. In lieu of other data, these settling column measurements were used to estimate a representative v_s for the St. Johns River site.

The settling column measurements for the St. Johns River site had been conducted at high concentrations of total suspended solids (20 percent); thus zone and compression settling were exhibited by the settling measurements. The interfacial velocity of the suspended sediment mass undergoing zone settling at the beginning of the settling column measurements was taken as an estimate of the particle setting velocity v_s. This interfacial velocity, determined from the slope of the curve of interfacial position versus time curve, was 5.143×10^{-3} ft/sec as listed in Table 3.

The available data allowed calculation of S and B for only three sets of data. Consequently a regression analysis on the two independent parameters S and B was not possible. However, the single parameter

$$S/B = (v_s T/h)/(b/h) = v_s T/b \tag{34}$$

which represents a normalized dimensionless setting velocity, correlated quite well with the source concentration C for the three sets of data. A regression analysis of the source concentration for the closed-bucket clamshell dredges at the St. John River, the Black Rock Harbor, and the Calumet River sites yielded the dimensionless equation

$$C/(\rho \times 10^{-6}) = 0.00235(B/S)^{3.033} = 0.00235\left[\frac{b}{v_s\ T}\right]^{3.033} \tag{35}$$

in which C is the open-bucket clamshell dredge source concentration. The linear correlation coefficient r^2 for the logarithmic equivalent form of Equation 35 is 0.979. Equation 36 can be closely approximated by

$$C/(\rho \times 10^{-6}) = 0.0023\left[\frac{b}{v_s\ T}\right]^{3} \tag{36}$$

A comparison of observed concentrations to those computed from Equation 36 is provided in Tables 3 and 6 and Figure 7.

Closed clamshell

The estimated source concentrations for the closed clamshell buckets are given in Table 3. For the St. Johns River, the source concentration is decreased in comparison to the open-bucket clamshell concentration, as might be expected. At the Lake City operation, however, the source concentration is higher for the closed-bucket clamshell operation. While the reason for this is not apparent, it may be because of the bucket size (the closed buckets were larger than the open buckets; (Table 2) and the bucket cycle time. While quantitative data were not reported on the cycle time T for the closed-bucket clamshell dredging operations, it is known that, because of the difficulty of forcing air out of the closed bucket, the cycle times for the closed-bucket

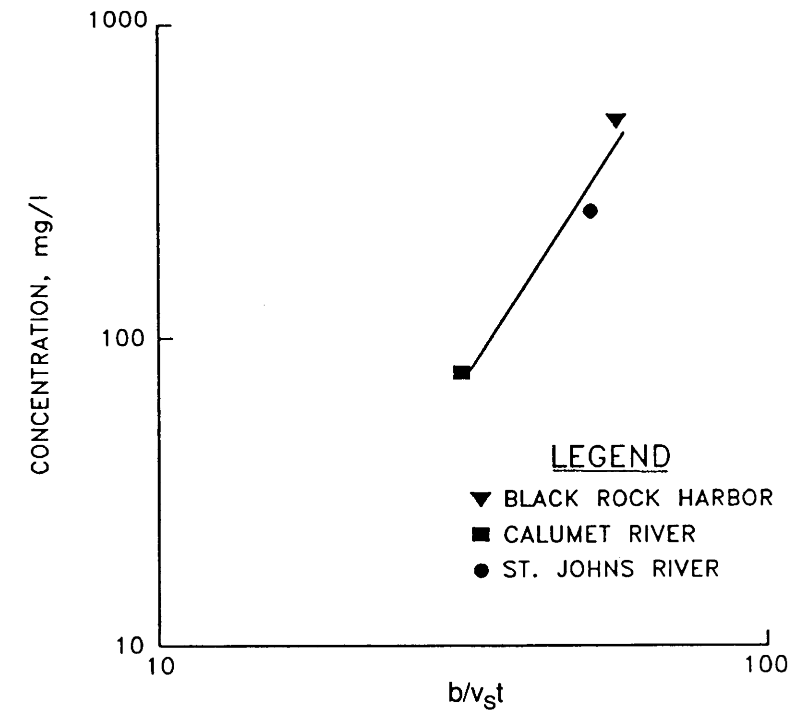


Figure 7. Open-bucket clamshell dredge correlation

clamshell dredging at both the Lake City and St. Johns River sites were at least as great as that for the open-bucket clamshells. It is also possible that the entrapped air in the bucket contributed to greater bucket impact on the bottom because the dredge operator may have attempted to overcome the air entrapment problems by trying to cause the bucket to drop more quickly than an open bucket. Sidecasting of the dredged sediment at the Lake City site may also account for the higher concentration levels observed with the closed-bucket operation.

Lack of data prevented an attempt to correlate closed-bucket clamshell resuspended sediment concentration with the S/B parameter of Equation 34; but the correlation of Equation 35 does suggest that cycle time, even for closed buckets, may be a crucial factor in the success of closed-bucket clamshell dredges in reducing resuspended sediment levels.

4 Suspended Sediment Source Strengths

Dredging operations are sources of resuspended sediment because of the hydraulic and mechanical actions of the dredge. Once introduced into the water column, resuspended sediments are advected and dispersed into the near and, ultimately, far field waters surrounding the dredge. Sediment resuspended as a consequence of the dredging can be described in terms of a resuspended sediment source and its associated source strength. Depending upon the type of dredge, different types of mathematical models can be used to describe this source and its strength.

Source strengths are mathematically inferred quantities and not directly measurable. The mathematical estimation of source strengths, even when incorporating field measurements on resuspended sediment concentrations, requires various assumptions. While these assumptions can be tested through application of mathematical models of resuspended sediment transport and deposition employing the estimated source strengths, the a priori descriptions of the resuspended sediment sources and their strengths provided below have not been verified and, therefore, must be considered as preliminary.

The estimation of resuspended sediment source strengths incorporates information about dredge characteristics and resuspended sediment concentrations in the immediate vicinity of the dredge or dredgehead. Of the several IOMT dredge studies described in the preceding chapters, only those for the cutterhead and clamshell dredges have sufficient information on which to formulate a source strength model. These studies, because they included more than one dredging operation for each of the dredge types, provide not only correlation of resuspended sediment concentration, but also demonstrate the specific influences of sediment properties, dredge characteristics, and dredge operating parameters. The remaining studies on the dustpan, matchbox, and hopper dredges do not provide such detail. Conceptual models for these latter type of dredges could be envisioned, but would be highly speculative and of limited utility since source concentrations could not incorporate dependencies on dredge characteristics and sediment properties.

Features of Source Model Structure

The strength of the resuspended sediment source, designated as R, is the temporal rate at which mass (or weight) of sediment is introduced into the near field waters surrounding a dredge as a consequence of a dredging activity. This source strength, as used here, describes the resuspended sediment in excess of background levels; it is assumed that the source strength is independent of such background suspended sediment levels.

The introduction of sediment into the water immediately surrounding the dredge represents a mass (or weight) flux of resuspended sediment originating from the source. This flux can be expressed in terms of the product of representative concentrations and velocities distributed over a source surface or boundary. Calculation of the resuspended sediment source strength from actual dredging data therefore requires a description of (a) the geometry of the source and source boundary surfaces, (b) the fluid velocity structure or fluid movement at the source boundaries, and (c) the resuspended sediment concentrations at the source boundaries.

Source geometry

For mathematical modeling and purposes of analytical analyses, a source may be conceived as being concentrated at a point, along a line, or over a surface. The choice of the geometric shape for a mathematically idealized source is based upon the physical system being described and mathematical convenience. Practical definition of source geometry must recognize the type of data (field data in the present study) from which velocities and sediment concentrations in and around the source are estimated. Because there is a practical limit upon how small a region around a particular dredge can be sampled, it is necessary to define the source strength using an approximating geometry for the source. Different types of source geometries of finite size, i.e., different source volumes, are therefore used in describing the source strengths for various types of dredges.

Source concentration

Correlations for resuspended sediment concentrations in the immediate vicinity of a dredge or dredgehead have been provided in Chapter 3 of this report for both cutterhead and clamshell dredges. These concentration correlations are functions of dredge characteristics, dredge operation, and sediment characteristics. The concentrations predicted by these correlations are the concentrations presumed to exist on the surface of the conceptualized source volume. Source volumes are defined so as to be consistent with the geometric assumptions made in deduction of these concentrations from field studies. For the cutterhead dredge, the concentrations are those immediately surrounding the cutterhead itself; for the clamshell dredge, these concentrations are the vertical average concentrations about the axis of the vertical motion of the clamshell bucket.

Velocity structure

The source models given below use a velocity that represents a fluid motion creating a transporting flux of resuspended sediment away from the surface of the source volume. This velocity, in general, is assumed to be the net result of the particular velocities induced by the operation and motion of the dredge bucket or dredgehead. Velocities induced by tides, currents, or similar external fluid motions are not directly included because the velocity field in the vicinity of the dredge is modified and disrupted by the dredge operation. The fluid velocity in the near field about the dredge is a localized velocity field defined in large measure by the configuration of the dredge and dredgehead or bucket motion.

Model coefficients

Mathematical models of hydraulically related phenomena, such as sediment resuspension, often incorporate unknown coefficients to account for effects or parameters not readily quantified. Ultimate use of such models requires a determination, usually by physical experimentation or field measurements, of those coefficients. The models formulated here limit the use of such coefficients for the following reason: the intended use of the present source strength models is to provide a priori estimates of resuspended sediment source strengths that can be initially used for numerical modeling of the resuspended sediment transport process, and, in addition, assist in identifying parameter groupings that characterize the effects of source strengths. A priori estimation cannot incorporate unknown coefficients; thus models must be formulated which, although possibly crude, incorporate parameters that are generally known or can be reasonably estimated.

Cutterhead Dredge

Source volume geometry

The resuspended sediment source volume geometry for a cutterhead suction dredge is taken as the dredgehead, approximated in its shape by a semi-ellipsoid with its minor axis and major axis equal to the maximum radius and length, respectively, of the cutterhead. This geometry is the same as that previously used to define the inwardly directed cutterhead suction intake velocity V_i and characteristic cutterhead size L.

Because of the washoff of sediment from the cutterhead, there develops a zone of resuspended sediment concentration C about the cutterhead, where the concentration C is given by the model of Equations 1 through 3. As a consequence, the swinging motion of the cutterhead creates a moving resuspended sediment source volume of magnitude V_{ch} with a volume average concentration C. While the calculation of the concentration in this zone is based upon the semi-ellipsoid source volume, the actual volume over which the concentration C may typically exist may occupy a volume larger than V_{ch}. The vertical extent of this volume is $(1 + k_{ch})D_{ch}$, while the length of this volume in the direction of the axis of the cutterhead is $(1 + k_{ch}^{'})L_{ch}$; both k_{ch} and $k_{ch}^{'} \leq 1.5$, where k_{ch} and $k_{ch}^{'}$ are size factors for the diameter and length of the cutterhead, respectively. In shallow waters where $(1 + k_{ch})\ D_{ch}$ exceeds the depth of the water, the vertical extent of the zone where the concentration is C would be limited by the depth of water.

Velocity structure

The motion of the cutterhead blades relative to overlying waters and eddy-induced motions behind the swinging cutterhead ladder wash sediment from the cutterhead blades and disperse it into the overlying waters. The rate at which the washing proceeds and the rate at which water is sweeping by the cutterhead due to the combined motion of the swinging ladder arm and the cutterhead blades is characterized by the net velocity V_t of the cutterhead blades near the top of the cutterhead rotation. Thus, similar to the deductions of Chapter 3,

$$V_t = V_c + V_s \qquad \textit{for overcutting} \tag{37}$$

$$V_t = V_c - V_s \qquad \textit{for undercutting} \tag{38}$$

While V_t is based upon the vector summation of velocities V_c and V_s at the top of the cutterhead, this velocity is viewed as a representative velocity at which resuspended sediment is generally introduced into the water immediately surrounding the cutterhead because of the combined motion of the cutterhead ladder arm and the rotating cutterhead. That is, for evaluation of source strength, V_t is a representative washoff speed tending to convey resuspended sediment away from the trailing side of the cutterhead.

Source strength

At any moment during the period of swing of the cutterhead ladder arm, the total mass flux of resuspended sediment emanating from the semi-ellipsoidal source volume is the result of the resuspended sediment passing across a surface in the plane orthogonal to the motion of the cutterhead ladder arm, i.e., across a plane of height $(1 + k_{ch})D_{ch}$ by length $(1 + k_{ch}^{'})L_{ch}$. Thus the source strength is

$$R = C\ V_t[1 + k_{ch}]D_{ch}[1 + k'_{ch}]L_{ch} \tag{39}$$

in which C is given by Equations 1 through 3. If C is in mg/ℓ, V_t in m/sec, and L_{ch} and D_{ch} in m units, then R will be g/sec units. If C is in mg/ℓ units while V_t is in ft/sec and L_{ch} and D_{ch} are in f units, then R will be in (mg/ℓ)(ft^3/sec) units, where 1 (mg/ℓ)(ft^3/sec) = 0.0283 g/sec.

Source strengths as computed from Equation 39 for some representative parameter values at the Savannah River, James River, and Calumet Harbor IOMT dredge sites are listed in Table 7.

Clamshell Dredge

Defining the resuspended source strength for the clamshell dredge requires relating resuspended concentration conditions to characteristics of the clamshell bucket and its operation. Resuspended sediment concentrations are related to these characteristics by Equation 36 for the open-bucket clamshell dredge. A corresponding equation was not developed for the closed-bucket clamshell dredge. Consequently, no attempt is made to identify the source strength for a closed-bucket clamshell dredge. However, should such a correlation be identified, its use to define dredge source strength would likely track that for the open clamshell bucket dredge.

Source geometry

The source geometry for a clamshell dredge is idealized as a cylindrical column of vertical height equal to the depth of water h in which the clamshell dredge is operating. Because a clamshell bucket is approximately square in the horizontal plane with area b^2 and, as given by Equation 32, has an approximate volume of $b^3/2$, the effective cross-sectional area of the cylinder in the horizontal plane is taken as b^2 while its perimeter is taken as $4b$, (Table 3). Note that the ratio of this effective cross-sectional area to perimeter is $b/4$, just as it would be for a circular cylinder. This geometry is only approximate since turbulent mixing will cause the resuspended sediment to occupy a volume larger than the idealized cylindrical source volume. The increased volume can be approximately accounted for by increasing the effective size of the bucket; this bucket size modification can be done after the resuspended sediment source strength for the actual bucket size is determined. Thus the development to follow first assumes that the actual bucket size is used to describe the source volume and resulting source strength. A postanalysis adjustment to the computed source strength is then made to account for the increase in effective bucket size due to turbulent mixing.

Because of the way it was derived from field data, the concentration given by the correlation of Equation 36 is the temporal vertical average concentration in the idealized center of the clamshell dredge; by assumption, this center corresponds to the vertical axis of the cylindrical source volume about the axis of rise and fall of the clamshell bucket. It is recognized that as dredging progresses this axis may slowly move, but such movement is not specifically accounted for in the following development.

Fluid and suspended sediment motions

The rising and falling motion of the clamshell bucket produces a pumping type of motion, periodically forcing sediment-laden waters from the source volume. This motion is responsible for the introduction of resuspended sediment into the near field about the dredge. Effects of currents, if present, would be accounted for in the far field modeling, which might use the source strength model to be developed in the following.

The start of a typical cycle of bucket motion can be conveniently taken as the time of bottom impact of a falling bucket; at this moment, time $t = 0$. The fluid motions resulting in the ejection of sediment outward across the cylindrical source volume surface can then be described in terms of the sequence of events over the time of a full cycle of bucket operation from $t = 0$ to $t = T$, where T can be decomposed into the following fractions of total cycle time:

f_u = fraction of the cycle time over which the bucket is rising in the water column

f_d = fraction of the cycle time over which the bucket is falling in the water column

f_b = fraction of the cycle time for which the bucket rests on or is dragged along the bottom

f_o = fraction of the cycle time for which the bucket is completely out of the water

where

$$f_u + f_d + f_b + f_o = 1 \tag{40}$$

Note that as a practical matter, f_b is usually nearly 0.

At time $t = 0$, bottom sediment is loosened by the bucket impact and the bucket claws gather sediments into the bucket; at time $t = f_bT$, the bucket begins to move upward. It is assumed that loosened materials not taken into the bucket remain near the bottom and do not significantly contribute to the sediment that passes across the surface of the source volume. The source of sediments moving across the surface of the source volume are assumed to be primarily those draining from the bucket because of bucket leakage, washoff, or overflow as the bucket is lifted upward at an assumed constant velocity v_u, where

$$v_u = h/(f_u\ T) \tag{41}$$

As the bucket is lifted upward, sediments draining from the bucket fill the water column below the bucket. Because of the induced turbulence, the resuspended sediments are uniformly mixed in the water column below the bucket. When the bucket finally breaks free of the water surface at time $t = (f_u + f_b)T$, the entire cylindrical source volume is filled with resuspended sediment with an average concentration C_u. In this idealized view, the waters above the bucket remain free of resuspended sediments. The mass rate r of sediment drainage from the bucket is assumed to be constant, so that at any time t the mass m_u of sediments in the water column below the bucket is given by

$$m_u = r\ (t - f_b T) \tag{42}$$

The volume over which this mass of sediment is distributed is given by $v_u\ (t = f_b T)\ b^2$, from which it follows that the volume average concentration, say c_u, the concentration below the bucket during the rise, at any time during the period of bucket lift is

$$c_u = \frac{m_u}{\left[v_u\ b^2\ (t - f_b T)\right]} \tag{43}$$

But since

$$r = \frac{m_u}{(t - f_b T)} \tag{44}$$

from Equation 42,

$$c_u = \frac{r}{v_u\, b^2} \tag{45}$$

Thus the concentration c_u throughout the period of lift is a constant and therefore

$$C_U = c_u \tag{46}$$

This conceptual view of the accumulation of suspended sediments in the source volume neglects the return of sediments from surrounding waters because of the inward motion of fluid due to the lifting of the bucket. The neglect of this sediment recapture is considered reasonable because of the advection and dispersal of sediments away from the bucket during the next period of bucket fall.

Once the bucket begins to fall, at an assumed constant rate of v_d, where

$$v_d = h/(f_d T) \tag{47}$$

all the suspended sediment beneath the bucket in the source volume at the time $t = (f_b + f_u + f_o)T$ must be ejected from the source volume by the end of the cycle at $t = T$ when the bucket reaches the bottom if it is assumed the water directly above the bucket remains essentially devoid of suspended sediment. Bucket sediment washoff during the bucket fall is neglected; its magnitude is considered small in comparison to the sediments accumulated in the water column during the bucket rise. Because both the fall velocity of the sediments and the time $f_o T$ can be expected to be small, the concentration in the source volume at $t = (f_b + f_u + f_o)\,T$ is set equal to C_U, the concentration at $t = (f_b + f_u)T$. Consequently, the total suspended sediment mass ejected over the period of fall must be $C_U b^2 h$.

However, the sediment ejected is the strength of the source. Therefore the average source strength R over the complete cycle of the bucket motion must be

$$R = C_U\, b^2\, h/T \tag{48}$$

Thus to determine the source strength R, the concentration C_U must be determined.

Source concentration

The concentration given by the correlation of Equation 36 is the temporal vertical average concentration for the source; it defines this average concentration C in terms of bucket size and operation. Thus to determine the strength R given in Equation 48 in terms of bucket size and operation, it is necessary to express C_U in terms of the temporal vertical average concentration C. This is accomplished through the steps outlined in the following paragraphs.

From $t = (f_b + f_u + f_o)\,T$ to $t = T$, the bucket is falling at an assumed constant velocity v_d (Equation 47) forcing sediment-laden water outward and away from the source volume by flow across the source volume surface with a spatial average radial velocity v_r, where by continuity

$$v_r 4b\{h - v_d[t - (f_b + f_u + f_o)T]\} = v_d\, b^2 \tag{49}$$

(Note that the product of the radial velocity and surface area of the source volume is a constant because v_d is an assumed constant.) If it is assumed that the resuspended sediment concentration, say c_d, at any time during the bucket fall varies linearly from C_U at time $t = (f_b + f_u + f_o)T$ to some value C_T at time t $= T$, then it can be demonstrated, as follows, that

$$C_T = C_U \tag{50}$$

To demonstrate the equality of Equation 50, consider the following: if it is assumed all suspended sediment must be forced out of the source volume by the time the bucket reaches the bottom, the total sediment mass ejected during the duration of time f_dT must be C_Ub^2h. Because of the assumed linear variation of concentration, the concentration at any moment is

$$c_d = (1 - f')C_U + f'C_T \tag{51a}$$

where

$$f' = [(t/T) - (f_b + f_u + f_o)]/f_d = [(t/T) - (1 - f_d)]/f_d \tag{51b}$$

That is, $f' = 0$ when $c_d = C_U$ and $f' = 1$ when $c_d + C_T$. The instantaneous total mass flux, M_d, across the source volume surface becomes, in view of Equation 47

$$M_d = c_d \, v_d \, b^2 \tag{52}$$

Integrating Equation 52 over the period of bucket fall yields the total sediment mass, which must also equal the total sediment mass at the instant the bucket begins its downward motion; thus

$$\int_{f_b + f_u + f_o}^{1} T \, M_d \, d(t/T) = \int_{f_b + f_u + f_o}^{1} T \, c_d \, v_d \, b^2 \, d(t/T) = C_U \, b^2 \, h \tag{53}$$

Using c_d from Equation 51 in the integration of the second integral of Equation 53 results in, after simplification,

$$(1/2)(C_U + C_T) \, f_d \, T \, v_d \, b^2 = C_U \, b^2 \, h \tag{54}$$

or, substituting v_d from Equation 47,

$$C_t = C_U$$

which demonstrates the equality of Equation 50. The equality exists because of the assumption that c_d varies linearly during the period of bucket fall. Thus, the concentration is constant during the period of bucket fall.

Because of the equality demonstrated by Equation 50, the concentration conditions beneath the bucket can now be readily averaged over the vertical height of the source volume and the duration of the cycle time to yield the temporal vertical average concentration C_a of the resuspended sediment source. Since the bucket rises and falls at a constant rate and the resuspended sediment is assumed to be only below the bucket, this average is computed to be

$$C_a = [(1/2) \, f_u + f_o + (1/2) \, f_d] C_U \tag{55a}$$

or

$$C_U = \frac{2C_a}{(f_u + 2 \, f_o + f_d)} \tag{55b}$$

Consequently the source strength becomes, using Equation 48

$$R = b^2\ (h/T)\frac{2C_a}{(f_u + 2\,f_o + f_d)} \tag{56}$$

The average concentration C_a computed in Equation 55a is based upon a source volume with cross-sectional area b^2, but, as previously noted, the resuspended sediments, because of turbulent mixing, are not restricted to the volume directly beneath the bucket. Because of mixing, the effective cross-sectional area of the source volume can be described as $(1 + k_{cb})b^2$, where k_{cb}, the size factor for the diameter of the clamshell bucket, is an empirical or experimentally estimated factor. Observations by Bohlen (1978) suggest that $1 + k_{cb}$ might on the order of 2 or 3. Because of this increased volume size, the average concentration C that would be actually observed in the source volume region would be less than C_a because the mass assumed to be in the area b^2 would be in fact spread over the area $(1 + k_{cb})b^2$. Thus, Equation 56 is modified to

$$R = 2b^2(h/T)(1 + k_{cb})\frac{C}{(f_u + 2\,f_o + f_d)} \tag{57}$$

The concentration of C of Equation 57 is also the concentration of Equation 36, the observed source concentration in the immediate vicinity of the bucket. Thus using the correlation of Equation 36,

$$R/(\rho \times 10^{-6}) = 0.0023b^2(1 + k_{cb})(b/v_sT)^3 \left[\frac{2(h/T)(1 + k_{cb})}{(f_u + 2\,f_o + f_d)}\right] \tag{58}$$

Some source strengths for representative values of clamshell dredge parameters as computed from Equation 37 are listed in Table 6. The parameters selected correspond to the open clamshell dredges studied in the IOMT program whose characteristics have been listed in Table 3.

5 Summary

Sediment resuspension by dredging is of concern because of the potential release of contaminants from bottom sediments, alteration of the physical and chemical characteristics of overlying waters, and subsequent resettling of sediments in environmentally sensitive areas. Bottom sediments introduced into overlying waters in the immediate vicinity of an operating dredge are advected and dispersed about the area of dredging by dredging-induced fluid motions and ambient currents and tides. This study focuses upon the near field area immediately surrounding a dredge and only incidentally considers points in the more distant far field. Because of the complexity of dredging-induced resuspension, both field measurements and mathematical modeling are used to describe the resuspension and subsequent transport processes.

Field measurements on dredging-induced resuspended sediment concentrations at nine inland and coastal dredging sites across the United States have been previously made, over the period of 1982 to 1985, under the Improvement of Operation and Maintenance (IOMT) Research Program. The dredge types studied were the cutterhead suction dredge at the Calumet Harbor, James River, and Savannah River sites, the matchbox dredge at the Calumet Harbor site, the dustpan dredge at the James River site, the hopper dredge with and without overflow at the Grays Harbor site, the open-bucket clamshell dredge at the Black Rock Harbor, Calumet River, Duwamish Waterway, Lake City, and St. Johns River sites, and the closed-bucket clamshell dredge at the Lake City and St. Johns River sites. These data were examined in this study for two purposes: (a) estimation of the dredging-induced resuspended sediment concentrations at or very near the actual point of dredging as a function of the dredge and dredge operating characteristics and sediment properties and (b) development of mathematical models providing a priori estimates of the temporal rate of sediment mass generation by the dredge at the point of dredging. The resulting correlations are based upon field data limited by both quality and availability. Further, the mathematical models proposed for sediment generation rates are based upon a combination of the concentration correlations and physical reasoning and assumptions; consequently, these models must be viewed as rudimentary and unverified.

Resuspended sediment concentrations at various points in the flow field about a dredge were obtained from field measurements by subtracting estimated background concentrations (i.e., concentrations that would exist in the absence of dredging) from measured total suspended sediment concentrations. These net concentrations were used to estimate the resuspension levels at the idealized dredging point. In the case of the cutterhead, dustpan, and matchbox dredges, data collected in very close proximity to the dredgehead could be used to make this estimation. The operational features of the remaining dredge types prevented field measurement extremely close to the dredging device (either a draghead or dredge bucket). For these dredges, concentration data at various distances from the dredge were averaged or smoothed in space and time to permit extrapolation of concentrations inward to the idealized dredging point.

Sediment resuspension by cutterhead suction dredges at a particular site is strongly dependent upon the swing speed of the ladder arm supporting the cutterhead, the rotational speed of the cutterhead blades, and the intake suction velocity at the cutterhead. Some directional sensitivity to ladder arm swing direction apparently exists and is reflected in higher resuspension levels in overcutting modes (when the cutterhead blades at their highest point are turning in the same direction as the ladder swing) versus those in an undercutting operating mode (when the cutterhead blades at their highest point are turning in the opposite direction to the ladder swing). As evidenced by resuspension levels at different study sites ranging, collectively, from approximately 2 to 300 mg/ℓ, resuspension is also influenced by the typical sediment particle size distribution of the sediments being dredged. These various parameters can be combined in dimensionless groups and correlated with resuspension concentrations observed close to the dredgehead. Cutterhead burial also affects the amount of resuspension. Both partial-cut and buried-cut dredging increase resuspension above that for full-cut dredging (when the top of the dredge cutterhead is at the mudline); a preliminary quantification of these impacts is provided.

The matchbox and dustpan dredges were proposed for field study in the IOMT program because of their reported potential to reduce resuspension levels in comparison to those produced by a cutterhead suction dredge. While matchbox and dustpan dredges rely upon fluid suction to collect bottom sediments as do the cutterhead suction dredges, neither the matchbox nor dustpan dredge employs rotating cutterhead blades to loosen and dislodge bottom sediments. However, difficulties in collecting data and inexperience in the actual operation of these two dredge types prevented a comprehensive quantitative evaluation of resuspension by these dredges at the study sites. The limited data are inconclusive as to the general effectiveness of these two dredge types in reducing resuspension in comparison to the resuspension produced by a cutterhead suction dredge.

The one hopper dredge studied in the IOMT program provided insight into the increases in resuspended sediment concentrations as a consequence of intentional overflow of the dredge hoppers. The estimated concentration level in the immediate vicinity of the dredgehead on the dragarm beneath the dredge was approximately 146 mg/ℓ which, when averaged over the vertical depth of overlying waters, yielded a value of about 13 mg/ℓ. When overflow from the dredge hoppers was allowed, the depth-averaged concentration increased about thirtyfold to 355 mg/ℓ.

Clamshell dredges use both closed- (i.e., watertight) and traditional open-bucket designs. The closed-bucket designs, two of which were studied at IOMT sites, seek to limit the overflow and leakage from the bucket as it is drawn upward in the water column and thereby lessen the introduction of sediment into the water column in comparison to the open-bucket clamshell, from which overflow and leakage are significant. However, difficulties in the operation and data collection for the closed-bucket dredges in the IOMT studies prevented a comprehensive evaluation of the closed-bucket designs. Estimated depth-averaged concentrations along the axis of bucket entry and withdrawal were in the 50- to 500-mg/ℓ range for both open and closed buckets. In the examination of open-bucket resuspension, certain parameters were concluded as being important in the characterization of the resuspension. Values for these parameters were not available for the closed buckets. Therefore, evaluation of impacts of clamshell dredge operation on resuspension focused upon the traditional open-bucket design.

Physical reasoning about the nature of the operation of an open-bucket clamshell dredge suggests that, among other factors, the bucket cycle time, bucket size, and sediment fall velocity are particularly important to the resuspension of sediment in the zone surrounding the axis of bucket rise and fall. A dimensionless grouping of these parameters could effectively correlate depth-averaged concentration data from the sites for which the values of these parameters were available. The correlation, furthermore, demonstrates a physically realistic dependence upon settling velocity, bucket size, and cycle time.

The amount of dredging-induced resuspended sediment can be described in terms of the temporal rate of sediment mass resuspended at the idealized point of the dredging. This sediment source is characterized in terms of a source volume of a particular geometry and source strength. Using a combination of physical reasoning, various reasonable but approximating assumptions, and the concentration correlations developed for the cutterhead and open clamshell dredges, resuspended sediment source models were formulated for both the cutterhead dredge and the open-bucket clamshell dredge. For the cutterhead dredge, the source geometry is an semi-ellipsoidal volume surrounding the cutterhead. For full-cut dredging, sediment is carried through the surface of this volume primarily by the net washoff of sediment from cutterhead blades produced by the combined motion of cutterhead blade rotation and cutterhead ladder swing. For the clamshell dredge, the source is a cylinder about the axis of bucket rise and fall. Sediment draining from a rising bucket accumulates in the cylinder and is then forced outward from the cylinder due to the downward motion of the falling bucket as it begins another cycle. The source strength is obtained by averaging the effects of this pumping-like motion over a typical cycle of the bucket operation.

The study provides an overview of resuspended sediment concentrations in the immediate, localized near field zone of certain types of dredges studied in the IOMT program. In the case of cutterhead dredges and open-bucket clamshell dredges, these concentrations have also been quantitatively correlated with parameters characteristic of the dredge, its operation, and the site of its operation. The models proposed for estimating resuspended sediment generation at the dredge provide insight into the impact of dredge and dredge operation on sediment resuspension. They also provide a starting point for a more thorough analytical evaluation of the entire resuspension, transport, and deposition process.

Well-defined and controlled field studies are needed to refine and improve the correlations identified and mathematical models proposed in this study and evaluate the effects of different types of dredges other than the cutterhead dredge and open-bucket clamshell dredge. Focused laboratory studies on the phenomena of cutterhead blade washoff and mixing around rising and falling cylinders may provide additional insight into the resuspension by, respectively, the cutterhead dredge and the clamshell dredge. The resuspended sediment source models developed in this study need to be critically examined through analytical or numerical modeling of the entire flow field around a dredge and comparison of the modeling results to field data measured at the IOMT sites either previously studied or that might be studied in the future.

References

Arctic Laboratories Limited, ESL Environmental Sciences Limited, EBA Engineering Consultants Limited, and Tekmarine, Inc. (1985). "Environmental assessment of dredging techniques," Report A.L.L.63-6, submitted to Environmental Protection Service, Environmental Canada, Yellowknife, N.W.T., Canada.

Barnard, W. D. (1978). "Prediction and control of dredged material dispersion around dredging and open-water pipeline disposal operation," Technical Report DS-78-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Bartos, M. J. (1977). "Classification and engineering properties of dredged material," Technical Report D-77-18, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Bohlen, W. F. (1978). "Factors governing the distribution of dredge-resuspended sediments." *Proceedings, 16th Coastal Engineering Conference, August 27 - September 3, 1978, Hamburg, Germany.* ASCE, New York, 2001-2017.

Havis, R. N. (1988). "Sediment resuspension by selected dredges," *Environmental Effects of Dredging*, Technical Note EEDP-09-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hayes, D. F. (1986a). "Development of a near field source strength model to predict sediment resuspension from cutter suction dredges," M.S. thesis, Mississippi State University, Mississippi State, MS.

Hayes, D. F. (1986b). "Guide to selecting a dredge for minimizing resuspension of sediment," *Environmental Effects of Dredging*, Technical Note EEDP-09-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hayes, D. F., McLellan, T. N., and Truitt, C. L. (1988). "Demonstrations of innovative and conventional dredging equipment at Calumet Harbor, Illinois," Miscellaneous Paper EL-88-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Herbich, J. B., and Brahme, S. B. (1991). "Literature review and technical evaluation of sediment resuspension during dredging," Contract Report HL-91-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

McLellan, T. N., Havis, R. N., Hayes, D. F., and Raymond, G. L. (1989). "Field studies of sediment resuspension characteristics of selected dredges," Technical Report HL-89-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Montgomery, R. L., and Raymond, G. L. (1984). "Overview of Corps research program on dredging contaminated sediments." *Management of bottom sediments containing toxic substances, Proceedings of the 8th U.S./Japan Experts Meeting, 8-10 November 1982, Tokyo, Japan.* T. R. Patin, ed., Water Resources Support Center, Fort Belvoir, VA, 381-402.

Petersen, M. (1986). *River engineering.* Prentice-Hall, Englewood Cliffs, NJ, 225-246.

Raymond, G. L. (1982). "Field study of the sediment resuspension characteristics of selected dredges." *Proceedings of the Fifteenth Annual Dredging Seminar, New Orleans, Louisiana, 20 October 1982, Texas A&M University.* J. B. Herbich, ed., Sponsored by the Center for Dredging Studies and Sea Grant College Program, Texas A&M University, College Station, TX, 1-32.

Raymond, G. L. (1984). "Techniques to reduce the sediment resuspension caused by dredging," Miscellaneous Paper HL-84-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Vann, R. G. (1983). "James River, Virginia dredging demonstration in contaminated material (kepone), dustpan versus cutterhead." *Management of bottom sediments containing toxic substances, Proceedings of the 7th U.S./Japan Experts Meeting, 2-4 November 1981, New York, NY.* Water Resources Support Center, Fort Belvoir, VA, 211-223.

Table 1
Summary of IOMT Field Studies

Study Site Field Sampling Period (Identification Symbol)	Dredge Type	Site Environment (Salinity Range)	Dredged Sediment Characteristics: ( ) = USCS Designation; d = Median Grain Diameter, mm; SG = Specific Gravity	Typical Current Range fps	Representative Background Concentrations, mg/ℓ, Near Surface Near Bottom
Calumet Harbor 10/24/85-10/26/85 10/21/85-10/22/85 (CH)	Cutterhead Matchbox	Freshwater Lake	Silty loam (ML) d = 0.043 mm; SG = 2.71	0.0 - 0.2	1 - 4 1 - 4
James River 4/27/82-4/29/82 6/7/82-6/14/82 (JR)	Dustpan Cutterhead	Estuary (< 1 ppt)	Very soft silty clay (mostly CH, some MH & SM) d = 0.0156 mm; SG = 2.73)	0.3 - 2.6	42 - 43 86 - 90
Savannah River 7/7/83 - 7/26/83 (SR)	Cutterhead	Estuary[1]	Soft, organic clay/silt mixture (OL, OH) d = 0.023;[2] SG[1]	0.1 - 2.6	17 67
Grays Harbor 11/2/83 - 11/10/83 (GH)	Hopper with & without overflow	Estuary (1 - 20 ppt)	Sandy silt (ML) d = 0.033 mm; SG = 2.72	0.4 - 2.5	12 - 28 54 - 60
Black Rock Harbor 5/2/83 - 11/10/83 (BR)	Open clamshell	Estuary (10 - 21 ppt)	Sandy organic clay (OH & CH) d = 0.043 mm;[3] SG = 2.39	0.2 - 0.8	45 69

(Continued)

[1] Unavailable data.
[2] Based upon regional data presented by Herbich and Brahme (1991) for Savannah Harbor Area.
[3] Average of three extrapolated grain size curves.

Table 1 (Concluded)

Study Site Field Sampling Period (Identification Symbol)	Dredge Type	Site Environment (Salinity Range)	Dredged Sediment Characteristics: ( ) = USCS Designation; d = Median Grain Diameter, mm; SG = Specific Gravity	Typical Current Range fps	Representative Background Concentrations, mg/ℓ, Near Surface Near Bottom
Calumet River 8/20/85 - 8/23/85 (CH)	Open clamshell	Freshwater lake	Silty organic clay/silt mixture (OL) d = 0.043 mm;[4] SG = 2.71[4]	< 0.2	9 - 12 10 - 18
Duwamish Waterway 3/26/84 (DW)	Open clamshell	Estuary (3 - 18 ppt)	Organic silt & clay with sand (MH, ML, CH, OH) d = 0.012 mm; SG = 2.62	0.0 - 1.1	11 26
Lake City 4/11/84-4/12/84 4/13/84-4/16/84 (LC)	Closed clamshell Open clamshell	Freshwater lake	Soft, organic clay/silt mixture (OL, OH) d[1]; SG[1]	0.0 - 2.0	2 - 5 10 - 27
St. Johns River 2/9/82, 2/11/82, 2/10/82 (SJ)	Closed clamshell Open clamshell	Estuary[1]	Silt (MH) SG = 2.4 d[1]	0.0 - 0.2	47 72

[4] Assumed to be same as Calumet Harbor.

Table 2
Summary of Dredge Characteristics

Site (Vessel Name)	Dredge Type (Suction Pipe Diameter, in.)	Cutterhead or Bucket Size	Clamshell Cycle Time or Operation Mode	Representative Maximum Dredging Depth, ft	Average Height of Sampling Tubes Above Center of Cutterhead, ft
Calumet Harbor (*Dubuque*)	Cutterhead (14)	3 ft diam x 2.5 ft long	Full cut	31	2.2
	Matchbox (14)	6 ft long x 7.5 ft max width x 2.67 ft high	Hydraulic suction	31	
James River (*Essex*)	Cutterhead (21)	5 ft diam x 5 ft - 1 in. long	Full cut	25	8.6
	Dustpan (21)	28 ft wide x 2 ft high inlet zone with side winglets	Bulldozer action without hydraulic jets	25	
Savannah River (*Clinton*)	Cutterhead (20)	6 ft diam x 5 ft long	Buried cut & partial cut	50	4.5
Grays Harbor (*Essayons*)	Hopper dredge with trailing arm suction	6,000-cu yd hopper with below-waterline overflow ports & 28-in. diam x 3.66-ft-long dragarm	10-15 min to reach overflow 10-15 min of overflow	27	
Black Rock Harbor (J.W. Lyons)	Open clamshell	10-cu yd bucket	40 sec Sweeping used	20	

(Continued)

Table 2 (Concluded)

Site (Vessel Name)	Dredge Type (Suction Pipe Diameter, in.)	Cutterhead or Bucket Size	Clamshell Cycle Time or Operation Mode	Representative Maximum Dredging Depth, ft	Average Height of Sampling Tubes Above Center of Cutterhead, ft
Calumet River	Open clamshell	10-cu yd bucket	60 sec with bucket drag bottom smoothing	27	
Duwamish Waterway	Open clamshell	--[1]	--[1]	30	
Lake City	Open clamshell Closed clamshell	3.5-cu yd bucket 4.5-cu yd bucket	60 sec --[1]	35 35	
St. Johns River	Open clamshell Closed clamshell	12-cu yd bucket 15-cu yd bucket	43 sec --[1] (No sweeping)	18 18	

[1] Unavailable data.

Table 3
Dredge and Site Parameters

Site	Idealized Volume for Dredgehead or Bucket, cu ft	Surface Area of Idealized Volume sq ft	Characteristic Length Scale for Dredgehead or Bucket, ft, *L* or *b*	Characteristic Settling Velocity 1,000 ft/sec	Observed Source Concentration C at Dredgehead or Bucket, mg/ℓ
Calumet Harbor (Cutterhead)	16.04	24.93	3.94	4.314	--[1]
James River (Cutterhead)	66.54	68.08	6.33	0.906	--
Savannah River	94.25	93.82	7.11	1.083[2]	--
Grays Harbor (without overflow)	10.42	21.98	4.38	2.556	146
Black Rock Harbor	540	--	8.14	3.507	520
Calumet River	540	--	8.14	4.314	75
Duwamish Waterway	--	--	--	0.318	80
Lake City					
open	189	--	5.74	--	55
closed	243	--	6.24		150
St. Johns River					
open	648	--	8.65		250
closed	810	--	9.32	5.143[3]	150

[1] Data unavailable.
[2] 2.5 specific gravity assumed.
[3] From settling column data analysis.

Table 4
Full-Cut Parameter Variation

Site and Type of Cut	Average u	Standard Deviation of u	F	$(L/d) \times 10^{-4}$
Calumet Harbor				
Full cut	-1.050	0.160	0.0892	2.7928
Savannah River				
Partial cut	-0.556	0.545	0.278	9.4223
Buried cut	1.229	0.598	16.94	
Estimated				
Full cut	-0.824[1]	--	0.15	
James River				
Full cut	1.914	0.439	82.1	12.368

[1] Computed from F.

Table 5
Full-Cut Dredging Function Correlation Statistics

Data Set	Standard Error in Estimate of log C	Number of Observations	r^2
Savannah River			
Partial cut	0.5321	25	0.2826
Buried cut	0.5914	27	0.3208
Partial & buried cut	0.5679	52	0.5661
James River	0.3976	21	0.003
Calumet Harbor	0.1491	12	0.7240
Savannah River partial & buried cut + Calumet Harbor	0.5153	64	0.5714
Savannah River partial & buried cut + Calumet Harbor + James River	0.5619	85	0.5563

Note: C = Resuspended sediment concentration; r^2 = correlation coefficient.

Table 6
Representative Resuspended Sediment Source Strengths for Open-Bucket Clamshell Dredges

Parameter	Black Rock Harbor	Site Calumet River	St. Johns River
b, ft	8.14	8.14	5.74
f_d[1]	0.4	0.4	0.4
f_o[1]	0.1	0.1	0.1
f_u h, ft	20	27	18
T, sec	40	60	43
$V_s \times 10^3$ (ft/sec)	3.507	4.314	5.143
$1 + k_{cb}$[1]	2	2	2
C, mg/ℓ	449	72	285
R, grams/sec	1,684	243	445

[1] Assumed values.

Table 7
Representative Resuspended Sediment Source Strengths For Cutterhead Suction Dredges

	Site		
Parameter	Calumet Harbor	James River	Savannah River
L/d	27,928	123,680	94,223
V_s/V_i	2	0.8	1.6
V_t/V_i	8	9	9
D	1	1	3.2
F	0.0892	82.1	16.94
u	-1.050	1.947	1.229
V	2.848	2.848	2.848
w	1.022	1.022	1.022
V_t, ft/sec	5	4	4
D_{ch}	3	5	6
L_{ch}	2.5	5.08	5
$1 + k_{ch}$	1.75	1.75	1.75
$1 + k'_{ch}$	1.25	1.25	1.25
C, mg/ℓ	5.4	411	594
R, grams/sec	13	2,858	4,413

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
August 1995

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
Dredging Induced Near Field Resuspended Sediment Concentrations and Source Strengths

5. FUNDING NUMBERS

6. AUTHOR(S)
Michael A. Collins

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
School of Engineering and Applied Science
Southern Methodist University
Dallas, TX 75222

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers, Washington, DC 20314–1000;
U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road, Vicksburg, MS 39180–6199

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
Miscellaneous Paper D-95-2

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Dredging in riverine, lacustrine, and estuarine environments introduces bottom sediments into overlying waters because of imperfect entrainment and incomplete capture of sediments resuspended during the dredging process and the spillage or leakage of sediments during subsequent transportation and disposal of the dredged sediments. Resuspension of bottom sediments and resulting dispersal may pose water quality problems in waters near dredging operations. Interest in this issue increases when the sediment being dredged is highly contaminated. Resuspension of sediments by dredging is affected by dredge characteristics, dredge operating conditions, properties of bottom and suspended sediments, and site–specific conditions such as bottom topography, ambient current, and depth. This report summarizes field studies conducted by the U.S. Army Corps of Engineers to assess the suspended sediment concentrations in the water column in the vicinity of various dredge types. These concentration data are combined with conceptual models for resuspended sediment source strength geometries and velocity patterns to estimate sediment source strengths for cutterhead and clamshell dredges. Although unverified, these models provide a starting point for a more thorough analytical evaluation of the entire resuspension, transport, and deposition process.

14. SUBJECT TERMS

Clamshell	Models	Source strength	Water quality
Cutterhead	Sediment	Suspended sediment	
Dredging	Sediment resuspension	Suspended solids	

15. NUMBER OF PAGES
229

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		